Fireball of the world's first thermonuclear explosion, Eniwetok Proving Grounds, November 1, 1952 (local time)

The Effects of

Nuclear Weapons

SAMUEL GLASSTONE
Editor

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Foreword

This book is a revision of "The Effects of Nuclear Weapons" which was issued in 1957. It was prepared by the Defense Atomic Support Agency of the Department of Defense in coordination with other cognizant governmental agencies and was published by the U.S. Atomic Energy Commission. Although the complex nature of nuclear weapons effects does not always allow exact evaluation, the conclusions reached herein represent the combined judgment of a number of the most competent scientists working on the problem.

There is a need for widespread public understanding of the best information available on the effects of nuclear weapons. The purpose of this book is to present as accurately as possible, within the limits of national security, a comprehensive summary of this information.

Robert S. McNamara

Secretary of Defense

Glenn T. Seaborg

Chairman
Atomic Energy Commission

Preface

When "The Effects of Atomic Weapons" was published in 1950, the explosive energies of the atomic bombs known at that time were equivalent to some thousands of tons (i.e., kilotons) of TNT. The descriptions of atomic explosions and their effects were therefore based on a so-called "nominal bomb" with an energy release equivalent to 20 kilotons of TNT. With the development of thermonuclear (hydrogen) weapons, having explosive energies in the range of millions of tons (i.e., megatons) of TNT, it became necessary to provide an entirely new presentation, "The Effects of Nuclear Weapons." The first edition of this work, issued in 1957, gave the best information then available concerning the effects on man and materials of nuclear weapons with explosive energy yields up to the equivalent of 20 megatons of TNT. After the cessation of U.S. nuclear tests at the end of October 1958, it was decided to prepare a revision of "The Effects of Nuclear Weapons" incorporating new information which had become available. Although the testing of nuclear weapons has since been resumed, the time is nevertheless opportune for the publication of this revised edition.

It is known that weapons having an explosive energy release of more than 20 megatons TNT equivalent can be produced. However, the limit of 20 megatons has been retained in the present volume, as in the original version. The expected effects of explosions of higher energy yield can be estimated by means of scaling laws. What are believed to be the most reliable scaling laws are given in the text, and with their aid it is possible to calculate, within the limitations mentioned below, the effects to be expected from a nuclear explosion of any prescribed TNT equivalent.

Extensive changes, both in information and presentation, have been made in this revision. The material on the protection against nuclear explosions has been rewritten from a new standpoint so as to bring out the principles involved. In this connection, quantitative data on weapons effects are given in simple tabular form suitable for ready reference. A new chapter has been included on the effects of nuclear explosions on radio communications and radar, and appendices dealing with nuclear weapons safety and methods for detecting distant nuclear explosions have been added. A list, with dates, times, and other unclassified information, of announced weapons tests, made by all countries is also provided.

Although every effort has been made to include the best possible information in this book, it should be kept in mind that, where numerical values are given, inevitable uncertainties are involved. For example, there are inherent difficulties in making exact measurements of weapons effects. The results are often dependent upon circumstances which are difficult, and sometimes impossible, to control even

in tests, and would certainly be unpredictable in the event of an attack. Furthermore, two weapons of different design may have the same explosive energy yield yet differ markedly in their actual effects. Where such possibilities exist, the text calls attention to the limitations of the data presented and of the appropriate scaling laws.

The phenomena of air blast, ground and water shock, thermal (heat) radiation, and nuclear radiations associated with nuclear explosions are very complex. The descriptions of these phenomena and their related effects are thus somewhat technical in nature. However, this book has been organized in such a manner as to serve the widest possible range of readers. With this end in view, most of the chapters are presented in two parts. The first consists of a general treatment of a particular topic in a less technical manner, whereas the second discusses some of the more technical aspects. The material is so arranged that the reader will experience no loss of continuity by the omission of any or all of the more highly technical sections. It is hoped that this format, which was also used in the previous edition, will permit the general reader to obtain a good understanding of each subject without the necessity for coping with the technical aspects with which he may not be concerned. On the other hand, the technical material is available for the use of specialists, such as architects, engineers, medical practitioners, and others, who may have need of such information in their work connected with defense planning.

Many organizations and individuals assisted in one way or another in the production of this revision of "The Effects of Nuclear Weapons," and their cooperation is acknowledged with gratitude. In particular, sincere thanks are due to Colonel T. A. Irving and Lieutenant J. L. Wray, Defense Atomic Support Agency, Headquarters; to Captain R. K. Parsons, Defense Atomic Support Agency, Field Command; and to R. L. Corsbie and L. J. Deal, U.S. Atomic Energy Commission, Division of Biology and Medicine, for their help in solving the numerous administrative, technical, and other problems which arose during the preparation of this book.

Advantage has been taken of this new printing to make some changes and additions, as well as to correct a few typographical errors. New laboratory measurements on the ignition of various fabrics and household materials (Tables 7.40 and 7.66) indicated that the fire hazard from thermal radiation was significantly less than implied in the first (April 1962) printing. It was felt, therefore, that the corrections in Chapter VII should be made at the earliest opportunity. Other changes of a minor nature have been introduced in this chapter to clarify certain aspects of the development and spread of fires. In addition, the compilation of Announced Nuclear Detonations in Appendix B has been extended through 1963.

Los Alamos, N. Mex. SAMUEL GLASSTONE
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chain reaction may then become possible with the same mass that was subcritical in the uncompressed state.

1.56 In a fission weapon, the compression may be achieved by means of a spherical arrangement of specially fabricated shapes of ordinary high explosive. In a hole in the center of this system is placed a subcritical sphere of fissionable material. When the high explosive is set off, by means of a number of detonators on the outside, an inwardly-directed "implosion" wave is produced. When this wave reaches the sphere of uranium (or plutonium), it causes the latter to be compressed. The surface to volume ratio of this compressed mass is then such as to make it supercritical. The introduction of neutrons from a suitable source can now initiate a chain reaction leading to an explosion.

Fission Products

1.57 Many different fission fragments, i.e., initial fission product nuclei, are formed when uranium or plutonium nuclei capture neutrons and suffer fission. This is because there are 40 or so different ways in which the nuclei can split up when fission occurs, so that about 80 different fragments are produced. There are some variations in the nature of the fission fragment nuclei and in their properties, depending on the particular substance undergoing fission and on the energy of the neutrons causing fission. For example, when uranium-238 undergoes fission as a result of the capture of neutrons of very high energy released in certain fusion reactions (§ 1.16) the products are somewhat different, especially in their relative amounts, from those formed from uranium-235 by ordinary fission neutrons.

1.58 Regardless of their origin, most, if not all, of the approximately 80 fission fragments are the nuclei of radioactive forms (radioisotopes) of well-known, lighter elements. The radioactivity is usually manifested by the emission of negatively charged beta particles (§ 1.26). This is frequently, although not always, accompanied by gamma radiation, which serves to carry off excess energy. In a few special cases, gamma radiation only is emitted.

1.59 As a result of the expulsion of a beta particle, the nucleus of a radioactive substance is changed into that of another element, sometimes called the "decay product." In the case of the fission fragments, the decay products are generally also radioactive, and these in turn may decay with the emission of beta particles and gamma rays. On the average, there are about three stages of radioactivity for each fission fragment before a stable (nonradioactive) nucleus is formed.

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The Radioactive Cloud

2.06 While the fireball is still luminous, the temperature, in the interior at least, is so high that all the weapon materials are in the form of vapor. This includes the radioactive fission products, uranium (or plutonium) that has escaped fission, and the weapon casing (and other) materials. As the fireball increases in size and cools, the vapors condense to form a cloud containing solid particles of the weapon debris, as well as many small drops of water derived from the air sucked into the rising fireball.

2.07 Quite early in the ascent of the fireball, cooling of the outside by radiation and the drag of the air through which it rises frequently brings about a change in shape. The roughly spherical form becomes a toroid (or doughnut), although this shape and its associated motion are often soon hidden by the radioactive cloud and debris. As it

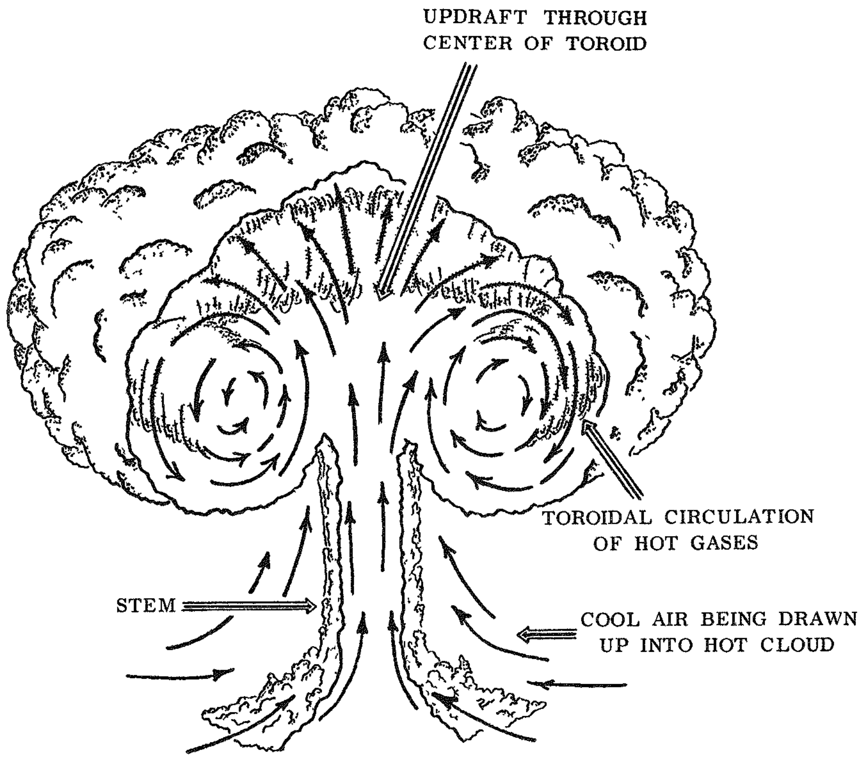

Figure 2.07a. Cutaway showing artist's conception of toroidal circulation within the radioactive cloud from a nuclear explosion.

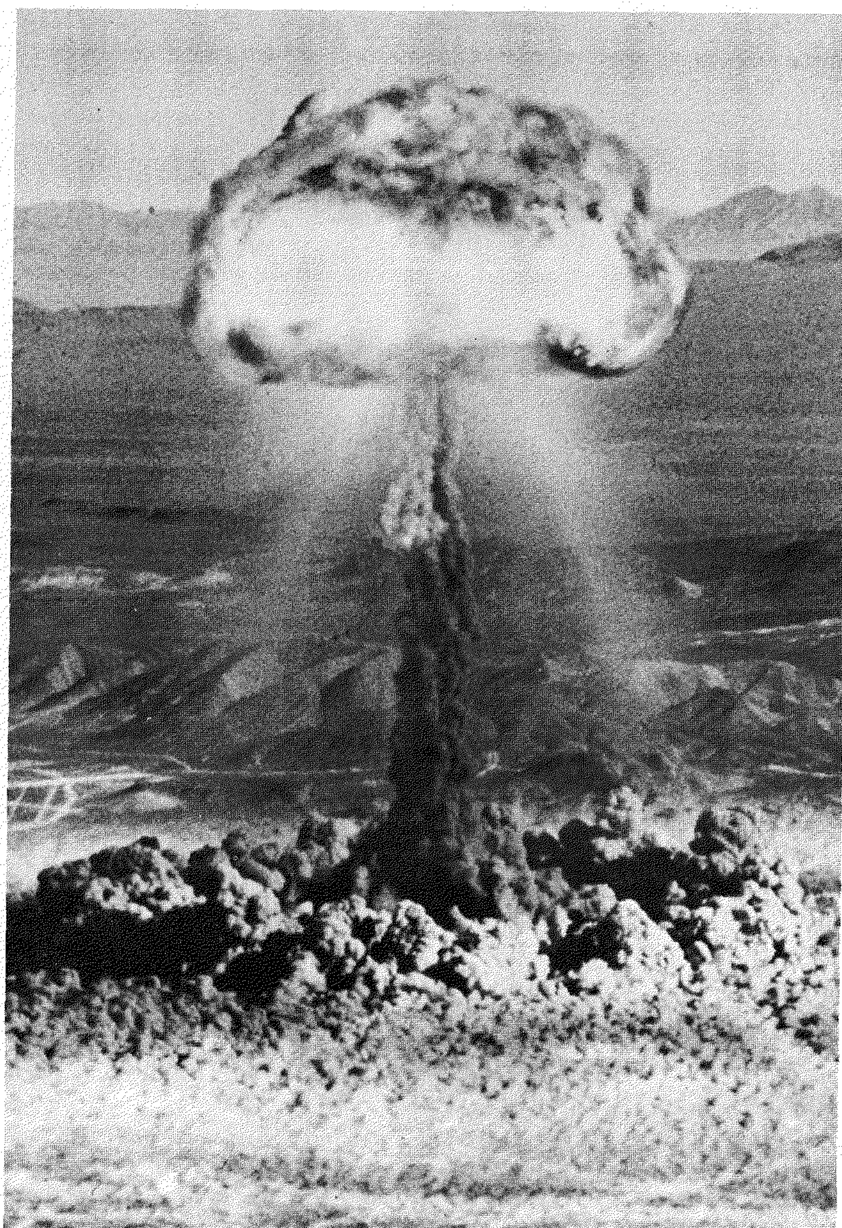

Figure 2.07b. Low air burst showing toroidal fireball and dirt cloud.

ascends, the toroid undergoes a violent, internal circulatory motion as shown in Fig. 2.07a. The formation of the toroid is usually observed in the lower part of the visible cloud, as may be seen in the lighter, i.e., more luminous, portion of Fig. 2.07b. During the course of the rapid ascent of the fireball, the toroidal motion slows and may be dissipated completely as the cloud rises toward its maximum height. In megaton explosions, the motion continues even after the maximum height is attained.

2.08 The color of the radioactive cloud is initially red or reddish brown, due to the presence of various colored compounds (nitrous acid and oxides of nitrogen) at the surface of the fireball. These result from the chemical interaction of nitrogen, oxygen, and water vapor in the air at the existing high temperatures and under the influence of the nuclear radiations. As the fireball cools and condensation occurs, the color of the cloud changes to white, mainly due to the water droplets as in an ordinary cloud.

2.09 Depending on the height of burst of the nuclear weapon and the nature of the terrain below, a strong updraft with inflowing winds, called "afterwinds", is produced in the immediate vicinity. These afterwinds can cause varying amounts of dirt and debris to be sucked up from the earth's surface into the radioactive cloud (Fig. 2.07b).

2.10 In an air burst with a moderate (or small) amount of dirt and debris drawn up into the cloud, only a relatively small proportion of the dirt particles will become contaminated with radioactivity. This is because the particles do not mix intimately with the weapon residues in the cloud at the time when the fission products are still vaporized and about to condense. In the case of a burst near the land surface, however, large quantities of dirt and other debris are drawn into the cloud at early times. Good mixing then occurs during the initial phases of cloud formation and growth. Consequently, when the vaporized fission products condense they do so on the foreign matter, thus forming highly radioactive particles (§ 2.23).

2.11 At first the rising mass of weapon residue carries the particles upward, but after a time they begin to fall slowly under the influence of gravity, at rates dependent upon their size. Consequently, a lengthening (and widening) column of cloud (or smoke) is produced. This cloud consists chiefly of very small particles of radioactive fission products and weapon residues, water droplets, and larger particles of dirt and debris carried up by the afterwinds.

2. 12 The speed with which the top of the radioactive cloud continues to ascend depends on the meteorological conditions as well as

on the energy yield of the weapon. An approximate indication of the rate of rise of the cloud from a 1-megaton explosion is given by the results in Table 2.12 and the curve in Fig. 2.12. Thus, in general, the cloud will have attained a height of 3 miles in 30 seconds and 4.5 miles in about 1 minute. The average rate of rise during the first minute or so is approximately 260 miles per hour. These values should be regarded as rough averages only, and large deviations may be expected in different circumstances.

2.13 The eventual height reached by the radioactive cloud depends upon the heat energy of the weapon, and upon the atmospheric conditions, e.g., moisture content and stability. The greater the

TABLE 2.12

RATE OF RISE OF RADIOACTIVE CLOUD

Height (miles)	*Time (minutes)*	*Rate of Rise (miles per hour)*
2	0. 3	300
4	0. 75	200
6	1. 4	140
10	3. 8	90
14	6. 3	35

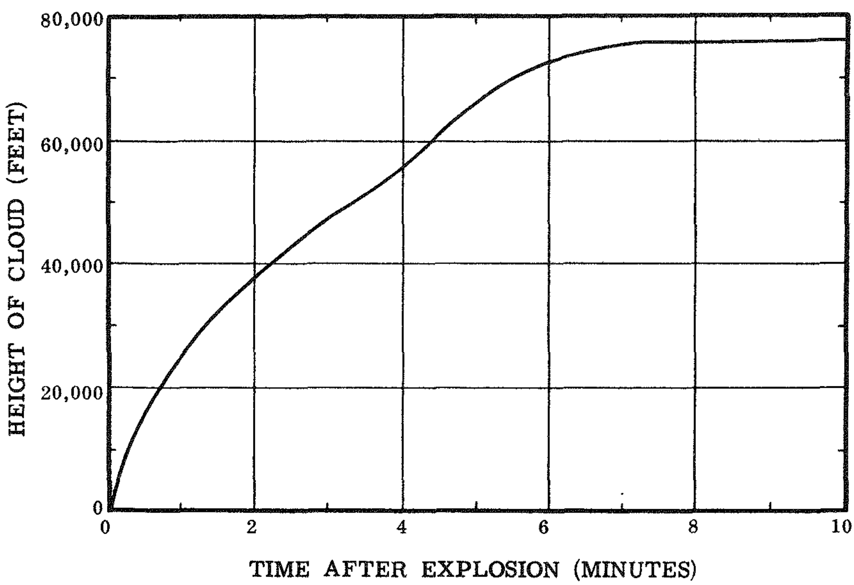

Figure 2.12. Height of cloud top above burst height at various times after a 1-megaton explosion for a moderately low air burst.

amount of heat generated the greater will usually be the upward thrust due to buoyancy and so the greater will be the distance the cloud ascends. The maximum height attained by the radioactive cloud is strongly influenced by the tropopause, i.e., the boundary between the troposphere below and the stratosphere above, assuming that the cloud attains the height of the tropopause.[2]

2.14 When the cloud reaches the tropopause, there is a tendency for it to spread out laterally, i.e., sideways. But if sufficient energy remains in the radioactive cloud at this height, a portion of it will penetrate the tropopause and ascend into the more stable air of the stratosphere.

2.15 The cloud attains its maximum height after about 10 minutes

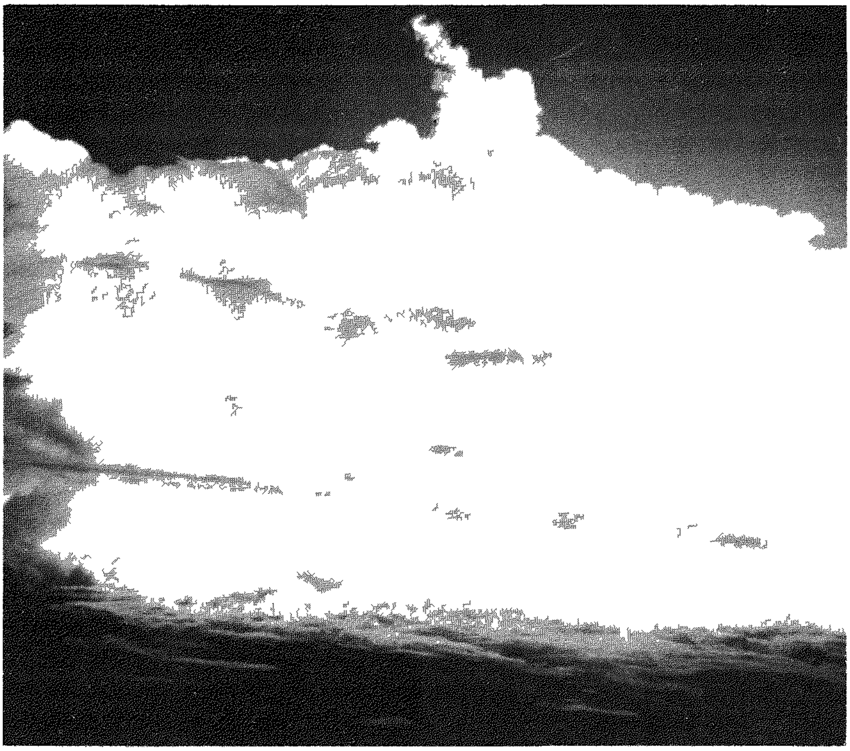

Figure 2.15 The mushroom cloud formed in a nuclear explosion in the megaton energy range, photographed from an altitude of 12,000 feet at a distance of about 50 miles.

[2] The tropopause is the boundary between the troposphere and the relatively stable air of the stratosphere. It varies with season and latitude, ranging from 25,000 feet near the poles to about 55,000 feet in equatorial regions (§ 9 147)

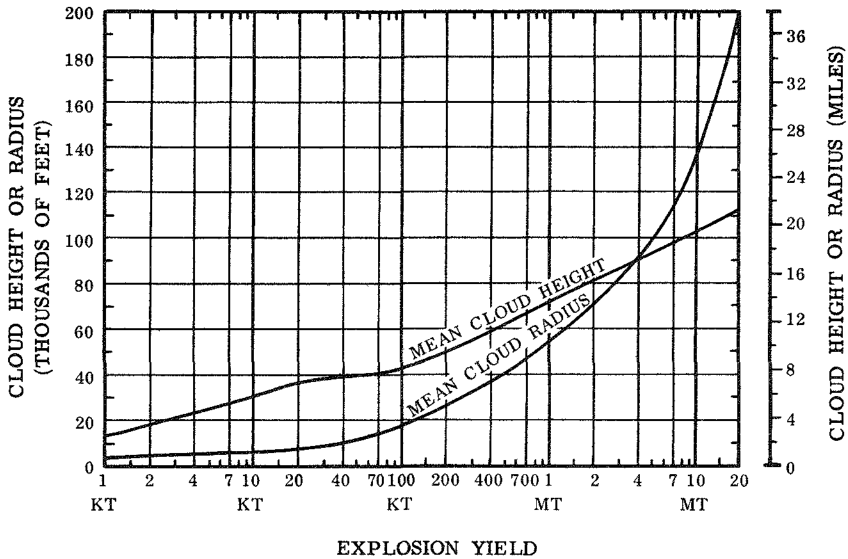

Figure 2.16. Average values of stabilized cloud height and radius as a function of explosion yield.

and is then said to be "stabilized." It continues to grow laterally, however, to produce the mushroom shape that is characteristic of nuclear explosions (Fig. 2.15). The cloud may continue to be visible for about an hour or more before being dispersed by the winds into the surrounding atmosphere where it merges with natural clouds in the sky.

2.16 The dimensions of the stabilized cloud formed in a nuclear explosion depend on the meteorological conditions, which vary with time and place. Approximate average values of cloud height and radius (at about 10 minutes after the explosion), attained in bursts at or near the earth's surface, for conditions most likely to be encountered in the continental United States, are given in Fig. 2.16 as a function of the energy yield of the explosion. The flattening of the height curve in the range of about 20- to 100-kilotons TNT equivalent is due to the effect of the tropopause in slowing down the cloud rise. For yields below about 15 kilotons the heights indicated are distances above the burst point but for higher yields the values are above sea level. For land surface bursts, the maximum cloud height is somewhat less than given by Fig. 2.16 because of the mass of dirt and debris carried aloft by the explosion.

Thermal and Nuclear Radiations in Underwater Burst

2.77 Essentially all the thermal radiation emitted by the fireball while it is still submerged is absorbed by the surrounding water. When the hot steam and gases reach the surface and expand, the cooling is so rapid that the temperature drops almost immediately to a point where there is no further appreciable emission of thermal radiation. It follows, therefore, that in an underwater nuclear explosion the thermal radiation can be ignored, as far as its effects on personnel and as a source of fire are concerned.

2.78 It is probable, too, that most of the neutrons and gamma rays liberated within a short time of the initiation of the explosion will also be absorbed by the water. But, when the fireball reaches the surface and vents, the gamma rays (and beta particles) from the fission products will represent a form of initial nuclear radiation. In addition, the radiation from the fission (and induced radioactive) products, present in the column, radioactive cloud, and base surge, all three of which are formed within a few seconds of the burst, will contribute to the initial effects.

2.79 However, the water fallout (or rainout) from the cloud and the base surge are also responsible for the residual nuclear radiations, as described above. For an underwater burst, it is thus less meaningful to make a sharp distinction between initial and residual radiations, such as is done in the case of an air burst. The initial nuclear radiations merge continuously into those which are produced over a period of time following the nuclear explosion.

Chronological Development of a Shallow Underwater Burst

2.80 The series of drawings in Figs. 2.80a, b, c, d, and e, which are shown on pages 92 to 96, at the end of this chapter, give a schematic representation of the chronological development of the phenomena associated with a shallow, underwater burst of a 100-kiloton nuclear bomb. The data supplement the information relating to a 20-kiloton explosion given above. Essentially all the effects, other than the shock front and the nuclear radiation, are visible.

Deep Underwater Explosion Phenomena

2.81 Because the effects of a deep underwater nuclear explosion are largely of military interest, the phenomena will be described in general terms and in less detail than for a shallow underwater burst.

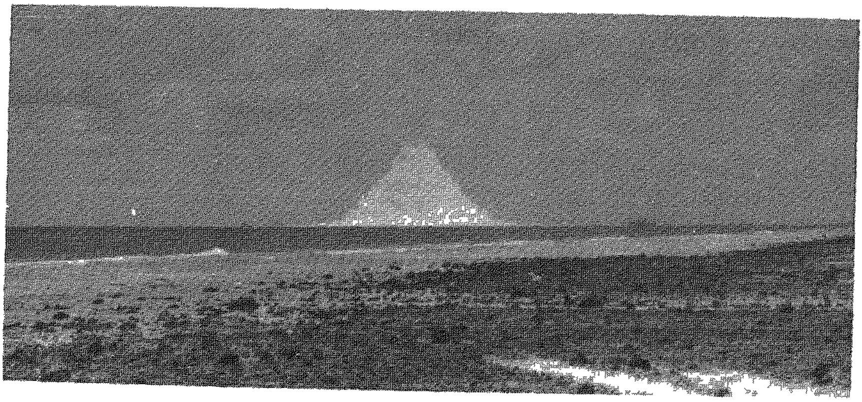

Figure 2.82a. Spray dome observed 5.3 seconds after explosion in deep water

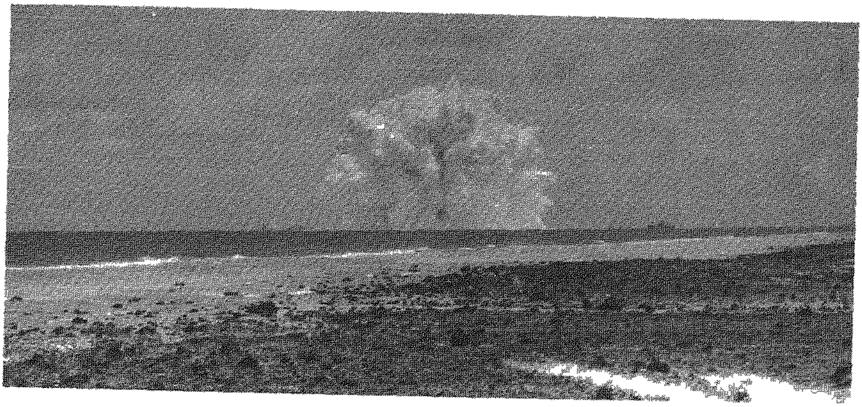

Figure 2.82b. Plume observed 11.7 seconds after explosion in deep water.

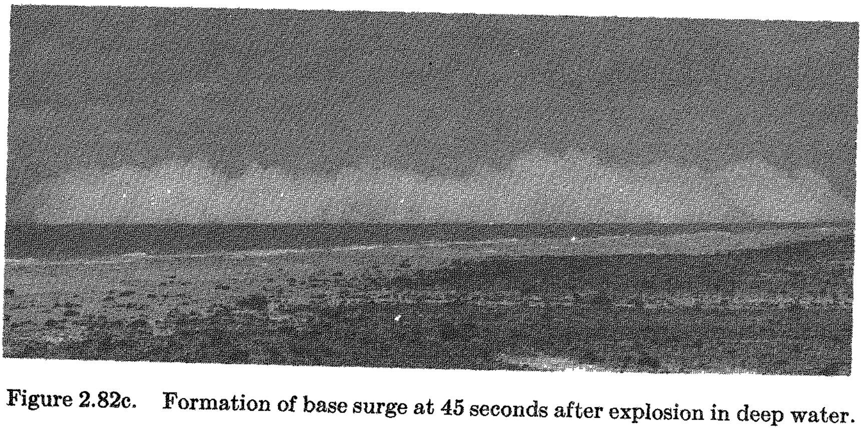

Figure 2.82c. Formation of base surge at 45 seconds after explosion in deep water.

The more important observations made at the WAHOO shot of Operation HARDTACK in 1958, when a nuclear weapon was detonated at a depth of 500 feet in deep water, will be summarized here.

2.82 The spray dome formed by the explosion rose to a height of 900 feet above the surface of the water (Fig. 2.82a). Shortly after the maximum height was attained, the hot gas and steam bubble burst through the dome, throwing out multiple plumes in all directions; the highest plumes reached an elevation of 1,700 feet (Fig. 2.82b). There was no airborne radioactive cloud, such as was observed in the shallow underwater BAKER shot. The collapse of the plumes created a visible base surge extending out to a distance of over 2½ miles downwind and reaching a maximum height of about 1,000 feet (Fig. 2.82c). This base surge traveled outward at an initial speed of nearly 75 miles per hour, but decreased within 10 seconds to less than 20 miles per hour.

2.83 There was little evidence of the fireball in the WAHOO shot, because of the depth of the burst, and only a small amount of thermal radiation escaped. The initial nuclear radiation was similar to that from a shallow underwater burst, but there was no lingering airborne radioactive cloud from which fallout could occur. The radioactivity was associated with the base surge while it was visible and also after the water droplets had evaporated. The invisible, radioactive base surge continued to expand and moved in the downwind direction. The deposited residual nuclear radiation was light and very little radioactivity was found on the surface of the water.

2.84 The hot bubble formed by the underwater nuclear detonation undergoes a series of pulsations, i.e., successive expansions and contractions, as it rises toward the surface. During the contraction phases some of the steam in the bubble condenses and part of the radioactive debris is removed by the liquid water droplets formed. When the bubble expands, however, and some of the water evaporates again, some of the radioactivity may return to the bubble. Hence, the radioactivity level of the base surge may be affected by the phase of the bubble when it breaks through the water surface. The activity levels of the radioactive base surge may thus be expected to vary widely, and although the initial dose rates may be very high, their duration is expected to be short.

DESCRIPTION OF UNDERGROUND BURSTS

Shallow Underground Explosion Phenomena

2.85 When a nuclear weapon is exploded under the ground, a fireball is formed consisting of extremely hot gases at high pressures,

including vaporized earth and weapon residues. If the detonation occurs at not too great a depth, the fireball may be seen as it breaks through the surface, before it is obscured by clouds of dirt and dust. As the gases are released, they carry up with them into the air large quantities of earth, rock, and debris in the form of a cylindrical column, analogous to that observed in an underwater burst. In

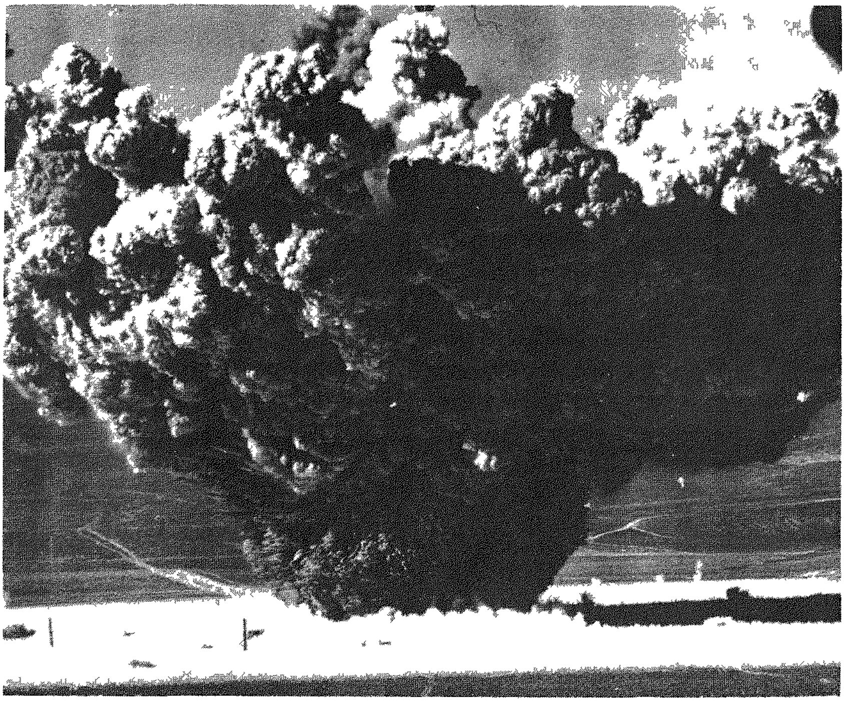

Figure 2.85. Shallow underground burst.

the underground test explosion at a shallow depth, made in Nevada in 1951, the column assumed the shape of an inverted cone, fanning out as it rose to cause a radial throw-out (Fig. 2.85). Because of the large amount of material removed by the explosion, a crater of considerable size was left in the ground.

2.86 It is estimated from tests made in Nevada that, if a 1-megaton weapon were dropped from the air and penetrated underground in sandy soil to a depth of 50 feet before exploding, the resulting crater would be about 300 feet deep and nearly 1,400 feet across. This means that approximately 10 million tons of earth and rock would be hurled upward from the earth's surface. The volume of the crater

and the mass of material thrown up by the force of the explosion will increase roughly in proportion to the energy of the weapon. As they descend to earth, the finer particles of soil may initiate a base surge, as will be described below.

2.87 The rapid expansion of the bubble of hot, high-pressure gases formed in the underground burst initiates a shock wave in the earth. This has a similar effect on a seismograph some distance away as an earthquake of moderate intensity. But, apart from the fact that the disturbances may originate at different depths, an underground nuclear explosion and an earthquake differ in an important respect. Theoretically, an explosion should produce an outward motion in all directions, whereas most earthquakes involve a sliding movement which should cause outward motion in some directions and inward motion in others. However, the actual motions do not always conform to these expectations.

2.88 As in an underwater burst, part of the energy released by the weapon in an underground explosion may appear as a blast wave in the air. The fraction of the energy imparted to the air in the form of blast depends primarily upon the depth of the burst. The greater the penetration of the weapon before detonation occurs, the smaller is the proportion of the shock energy that escapes into the air. If the explosion is fully contained there is, of course, no blast wave formed.

Base Surge and Fallout

2.89 When the material thrown up as a column of dirt in an underground explosion falls back to earth, it will, in many instances, produce an expanding cloud of fine soil particles similar to the base surge observed in the underwater Bikini BAKER test. For example, the early stages of a base surge formation can be seen in Fig. 2.89, which resembles Fig. 2.71 in many respects. The base surge of dirt particles moves outward from the center of the explosion and is subsequently carried downwind. Eventually the particles settle out and produce radioactive contamination over a large area, the extent of which will depend upon the depth of burst, the nature of the soil, and the atmospheric conditions, as well as upon the energy yield of the explosion. It is believed that a dry sandy terrain would be particularly conducive to base surge formation in an underground burst.

2.90 The radioactive cloud resulting from an uncontained underground explosion will inevitably include a very large amount of soil, rocks, and a variety of debris. There will, consequently, be a considerable fallout of contaminated matter. The larger pieces thrown

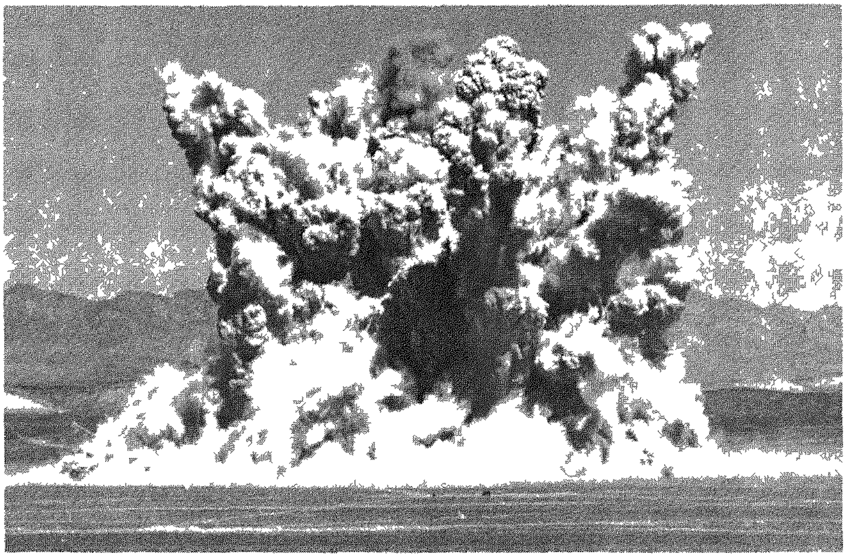

Figure 2 89. Base surge formation in a shallow underground burst

up by the explosion will be the first to reach the earth and so they will be deposited near the location of the burst. But the smaller particles will remain suspended in the air for some time and may be carried great distances by the wind before they eventually settle out.

Thermal and Nuclear Radiations in Underground Burst

2.91 The situation as regards thermal and nuclear radiations from an underground burst are quite similar to those described above in connection with an underwater explosion. As a general rule, the thermal radiation will be almost completely absorbed by the soil material, so that it does not represent a significant hazard Most of the neutrons and early gamma rays will also be removed, although the capture of the neutrons may cause a considerable amount of induced radioactivity in various materials present in the soil. This will constitute a small part of the residual nuclear radiation, of importance only in the close vicinity of the point of burst The remainder of the residual radiation will be due to the contaminated base surge and fallout.

2.92 For the same reasons as were given in § 2.79 for an underwater burst, the initial and residual radiations from an underground burst

tend to merge into one another. The distinction which is made in the case of an air burst is consequently less significant in a subsurface explosion.

Chronological Development of a Shallow Underground Burst

2.93 The chronological development of some of the phenomena associated with an underground nuclear explosion, having an energy yield of 100 kilotons, at a shallow depth is represented by Figs. 2.93 a, b, c, and d. For convenience, these are given on pages 97 to 100 at the end of the chapter.

Deep Underground Explosion Phenomena

2.94 A deep underground explosion is one occurring at such a depth that there is little or no venting of the weapon debris through the surface of the ground. The following description is based on the observations associated with the RAINIER event of Operation PLUMBBOB in 1957, in which a 1.7-kiloton TNT equivalent nuclear device was detonated at a depth of 790 feet below the surface in a medium referred to geologically as "tuff." All of the radioactivity as well as the heat energy were contained in the ground. The phenomena can best be described in terms of four phases having markedly different time scales.

2.95 First, the energy of the nuclear explosion, which took place in a chamber 6 ft by 6 ft by 7 ft in dimensions, was released in less than a one-millionth part of a second, i.e., less than 1 microsecond. As a result, the pressure in the chamber rose to several million atmospheres within a few microseconds and the temperature reached about a million degrees. In the second (hydrodynamic) stage, which was of a few hundredths of a second duration, the chamber expanded under the influence of the tremendous pressures to produce a spherical cavity 62 feet in radius. At this stage the cavity was lined with a shell of molten rock about 4 inches thick. The shock from the explosion crushed the rock to a radius of 130 feet and fractured it to 180 feet. The shock continued outward, its amplitude decreasing with increasing distance until it became attenuated. Seismic signals were detected out to distances of several hundred miles and a weak signal was recorded in Alaska.

2.96 In the next phase, lasting for a period of seconds to minutes, the molten material flowed down the walls and collected at the

bottom of the cavity. Here it froze to form a glassy mass which contained 65 to 80 percent of the total radioactivity of the fission products; the remainder was distributed throughout the crushed zone. The third stage ended when the roof collapsed, thus enlarging the chamber upward for a distance of about 400 feet. The temperature then dropped as a result of expansion of the gases and the introduction of colder rock and other material. In the final (or long-term) stage, the heat gradually diffused outward and the radioactive material decayed in the usual manner.

2.97 Records, obtained at stations located 110 to 350 miles from the test site, showed that the seismic signal of the RAINIER shot was equivalent to that from an earthquake of magnitude 4.06 on the conventional Gutenberg-Richter scale; this would be described as a "minor" earthquake. Such a disturbance, originating from a movement of the earth's crust, should be perceptible to individuals as far as 60 miles from the epicenter. However, of the observers located 2½ miles from ground zero at the time of the RAINIER detonation, only a very few felt any ground motion.

SCIENTIFIC ASPECTS OF NUCLEAR EXPLOSION PHENOMENA [7]

INTRODUCTION

2.98 The events which follow the very large and extremely rapid energy release in a nuclear explosion are mainly the consequences of the interaction of the kinetic energy of the fission fragments and the thermal radiations with the medium surrounding the explosion. The exact nature of these interactions, and hence the directly observable and indirect effects they produce, that is to say, the nuclear explosion phenomena, are dependent on such properties of the medium as its temperature, pressure, density, and composition. It is the variations in these factors in the environment of the nuclear detonation that account for the different types of response associated with air, high-altitude, surface, and subsurface bursts, as described earlier in this chapter.

2.99 Immediately after the explosion time, the temperature of the weapon material is several tens of million degrees and the pressures are estimated to be many million atmospheres. As a result

[7] The remaining sections of this chapter may be omitted without loss of continuity.

of numerous inelastic collisions part of the kinetic energy of the fission fragments is converted into internal and radiation energy. Some of the electrons are removed entirely from the atoms, whereas others are raised to higher energy (or excited) states while still remaining attached to the nuclei. Within an extremely short time, perhaps a hundredth of a microsecond or so, the weapon residues consist essentially of completely and partially stripped atoms, many of the latter being in excited states, together with the corresponding free electrons. The system then immediately emits electromagnetic (thermal) radiation, the nature of which is determined by the temperature. Since this is of the order of several tens of million degrees, most of the energy will be in the soft X-ray region (§ 1.72, see also § 7.80).

2.100 The primary thermal radiation leaving the exploding weapon is absorbed by the atoms and molecules of the surrounding medium. Consequently the medium is heated and the resulting fireball re-radiates part of its energy as thermal radiation which lies mainly in the ultraviolet, visible, and infrared regions of the spectrum. The remainder of the energy contributes to the shock wave formed in the surrounding medium in the manner to be described below. Ultimately, essentially all the thermal radiation (and shock wave energy) is absorbed and appears as heat, although it may be dissipated over a large area. In a dense medium such as earth or water, the degradation and absorption occur within a short distance from the explosion, but in air the thermal radiation may travel considerable distances. The actual behavior depends on the air density, as will be seen later.

2.101 There is another mechanism, in addition to the one just described, for the transfer of part of the kinetic energy of the fission fragments to the surroundings. This arises from what is called "hydrodynamic coupling" of the explosion energy with the ambient medium. Because of the very high pressure within the exploding weapon, the residue, consisting of fission products and all other weapon materials, moves outward from the center of the explosion at a very high velocity. The random kinetic energy of the individual atoms, etc., is thus being converted into directed mass energy, that is, energy of motion of the mass of residues. After a few microseconds nearly all of the debris is contained in a moderately thin shell of high density called the "hydrodynamic front." Its initial temperature is about a million degrees and it is traveling at a speed of several hundred miles per second. When the hydrodynamic front reaches the ambient medium it acts like a fast-moving piston. Energy is thus transferred to the medium by impulse, and a compression wave, which rapidly becomes a steep-

fronted shock wave, as shown in Fig. 1.01, moves outward. The mass energy of the weapon debris is thus transferred to the surroundings as blast and shock.

2.102 It will be apparent from the foregoing descriptions that the kinetic energy of the fission fragments, constituting some 85 percent of the total energy released (§ 1.22), distributes itself between thermal radiation, on the one hand, and shock and blast, on the other hand, in proportions depending largely on the nature of the ambient medium. The higher the density of the latter, the greater the extent of the coupling between it and the hydrodynamic front of the exploding nuclear weapon. Consequently, when a burst takes place in a medium of high density, e.g., water or earth, a larger percentage of the kinetic energy of the fission fragments is converted into shock and blast energy than is the case in a less dense medium, e.g., air. At very high altitudes, on the other hand, where the air pressure is extremely low, only a small proportion of the kinetic energy of the fission fragments may appear in the shock wave. In any event, the form and amount in which this radiation is received at a distance from the explosion will also be dependent on the nature of the intervening medium.

Development of the Fireball in an Air Burst

2.103 The transfer of energy by radiation within a hot gas, e.g., from the hot interior to the cooler exterior of the fireball, takes place in the following manner. First, an atom, molecule, or ion absorbs a photon of the radiation (§ 1.70) and is thereby converted into a high-energy (or excited) state. The atom or other particle remains in the excited state for a short time and then reverts to its lower energy (or ground) state by the re-emission of a photon. This photon then moves off in a random direction with the velocity of light; it may then be captured by another atom, molecule, etc., and again re-emitted, and so on. The energy carried by the photon is thus transferred from one point to another within the gas.

2.104 If the mean free path of the radiation, i.e., the average distance a photon travels between interactions, is large in comparison with the dimensions of the gaseous volume, the transfer of energy from the hot interior to the cooler exterior of the gas will occur more rapidly than if the mean free path is small. This is because, in their outward motion through the gas, the photons with short mean free paths will be absorbed and re-emitted several times. At each re-emission the photon moves away in a random direction, and so the

effective rate of transfer of energy in the outward direction will be less than for a photon of long mean free path which undergoes little or no absorption and re-emission.

2.105 In the earliest stage of the expansion of the weapon residues the temperature is extremely high and the mean free path of the radiation is long compared to the dimensions of the volume of expanding residues. Consequently, the transfer of energy by radiation takes place rapidly within the mass of hot gas and the temperature throughout the material is uniform. This mass is therefore referred to as the "isothermal sphere" and represents the early stages of the fireball. Provided the ambient air is cold and has an appreciable density, the soft X-rays and ultraviolet radiation constituting the major part of the thermal radiation emanating from the isothermal sphere are absorbed or degraded in energy within a short distance. The surrounding air thus becomes extremely hot, with the result that the dimensions of the fireball increase rapidly.

2.106 At first, the shock front (§ 2.101) lags behind the radiation front, i.e., the surface of the fireball, because the mean free path of the radiation in the hot gas is so long that transfer of energy by radiation is more rapid than by mass motion. As the fireball expands and the energy is deposited in an ever increasing volume (and mass) of air, the temperature within the isothermal sphere falls. As a result, the mean free path of the radiation decreases and transfer of energy by radiation becomes less rapid. The shock front then begins to advance faster than the radiation front and soon the two coincide. The shock front continues to advance more rapidly than the radiation front and moves ahead of it at the time when the temperature of the isothermal sphere has fallen to about 300,000° C (540,000° F). This phenomenon is called "hydrodynamic separation." For a 20-kiloton explosion it occurs at about 0.1 millisecond (10^{-4} second) after the burst time when the fireball radius is roughly 40 feet.

2.107 As the shock front moves ahead of the isothermal sphere it causes a tremendous compression of the ambient air and the temperature is thereby increased to an extent sufficient to render the air incandescent. The fireball now consists of two concentric regions. The inner (hotter) region is the isothermal sphere of uniform temperature, and this is surrounded by a layer of luminous, shock-heated air at a somewhat lower, but still high, temperature. The surface of separation between the very hot core and the somewhat cooler outer layer is the radiation front.

2.108 The phenomena described above are represented schematically in Fig. 2.108; qualitative temperature profiles are shown at the

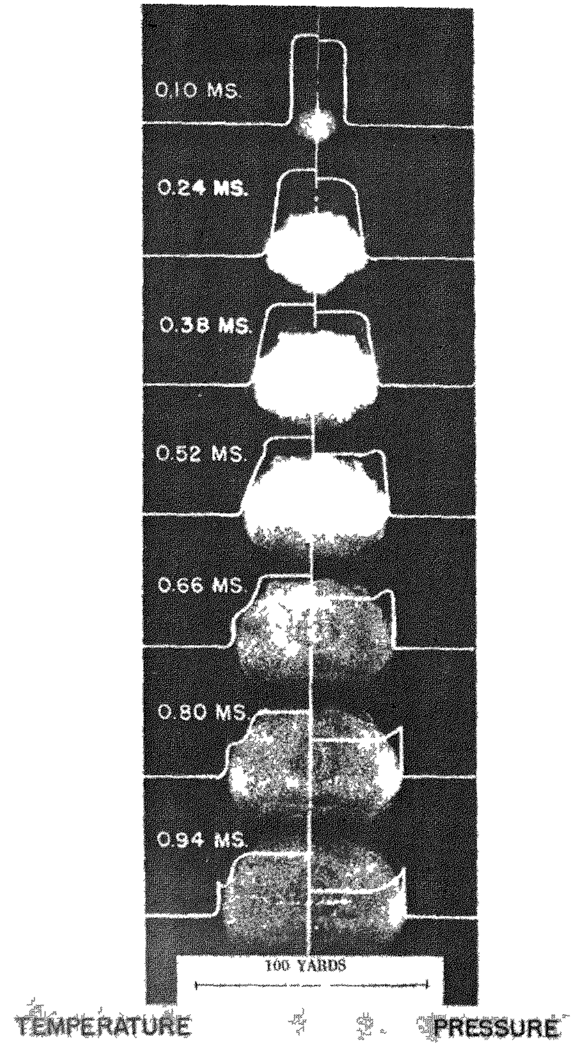

Figure 2.108. Variation of temperature and pressure in the fireball. (Times and dimensions apply to a 20-kiloton explosion.)

left and pressure profiles at the right of a series of photographs of the fireball at various intervals after the detonation of a 20-kiloton weapon. In the first picture, at 0.1 millisecond, the temperature is shown to be uniform within the fireball and to drop abruptly at the

exterior, so that the condition is that of the isothermal sphere. Subsequently, as the shock front begins to move ahead of the isothermal sphere, the temperature is no longer uniform, as indicated by the more gradual fall near the outside of the fireball. Eventually, two separate temperature regions form. The outer region absorbs the radiation from the isothermal sphere in the center and so the latter cannot be seen. The photographs, therefore, show only the exterior surface of the fireball.

2.109 From the shapes of the curves at the right of Fig. 2.108, the nature of the pressure changes in the fireball can be understood. In the isothermal stage the pressure is uniform throughout and drops sharply at the outside, but after a short time, when the shock front has separated from the isothermal sphere, the pressure near the surface is greater than in the interior of the fireball. Within less than 1 millisecond the steep-fronted shock wave has traveled some distance ahead of the isothermal region. The rise of the pressure in the fireball to a peak, which is characteristic of a shock wave, followed by a sharp drop at the external surface, implies that the latter is identical with the shock front. It will be noted, incidentally, from the photographs, that the surface of the fireball, which has hitherto been somewhat uneven, has now become sharply defined.

2.110 For some time the fireball continues to grow in size at a rate determined by the propagation of the shock front in the surrounding air. During this period the temperature of the shocked air decreases steadily so that it becomes less opaque. Eventually, it is transparent enough to permit the much hotter and still incandescent interior of the fireball, i.e., the isothermal sphere, to be seen through the faintly visible shock front (see Fig. 2.32). The onset of this condition at about 0.015 second after the detonation of a 20-kiloton weapon, for example, is referred to as the "breakaway."

2.111 Following the breakaway, the visible fireball continues to increase in size at a slower rate than before, the maximum dimensions being attained after about a second or so. The manner in which the radius increases with time, in the period from roughly 0.1 millisecond to 1 second after the detonation of a 20-kiloton nuclear weapon, is shown in Fig. 2.111. Attention should be called to the fact that both scales are logarithmic, so that the lower portion of the curve (at the left) does not represent a constant rate of growth, but rather one that falls off with time. Nevertheless, the marked decrease in the rate at which the fireball grows after breakaway is apparent from the subsequent flattening of the curve.

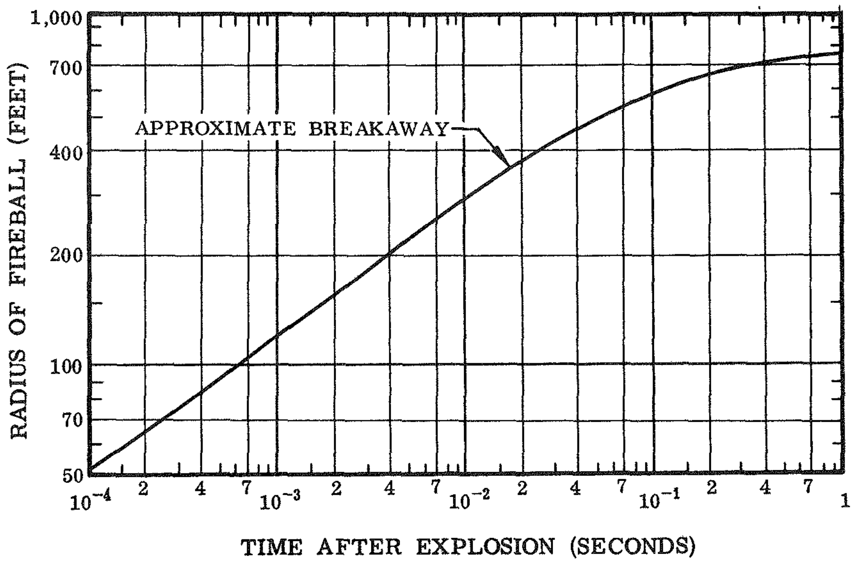

Figure 2.111. Variation of radius of luminous fireball with time in a 20-kiloton explosion.

Temperature of the Fireball

2.112 As indicated earlier, the interior temperature of the fireball decreases steadily, but the apparent surface temperatures, which influences the emission of thermal radiation, decreases to a minimum and then increases to a maximum before the final steady decline. This behavior is related to the fact that at high temperatures air both absorbs and emits thermal radiation very readily, but as the temperature falls below a few thousand degrees, the ability to absorb and radiate decreases.

2.113 From about the time the fireball temperature has fallen to 300,000° C, when the shock front begins to move ahead of the isothermal sphere, until close to the time of the first temperature minimum (§ 2.38), the expansion of the fireball is governed by the laws of hydrodynamics. It is then possible to calculate the temperature of the shocked air from the measured shock velocity, i.e., the rate of growth of the fireball. The variation of the temperature of the shock front with time, obtained in this manner, is shown by the full line from 10^{-4} to 10^{-2} second in Fig. 2.113, for a 20-kiloton explosion. However, photographic and spectroscopic observations of the surface brightness

of the advancing shock front, made from a distance, indicate the much lower temperatures represented by the broken curve in the figure. The reason for this discrepancy is that both the nuclear and thermal radiations emitted in the earliest stages of the detonation interact in depth with the gases of the atmosphere ahead of the shock front to produce ozone, nitrogen dioxide, nitrous acid, etc. These substances are strong absorbers of radiation coming from the fireball, so that the brightness observed some distance away corresponds to a temperature considerably lower than that of the shock front.

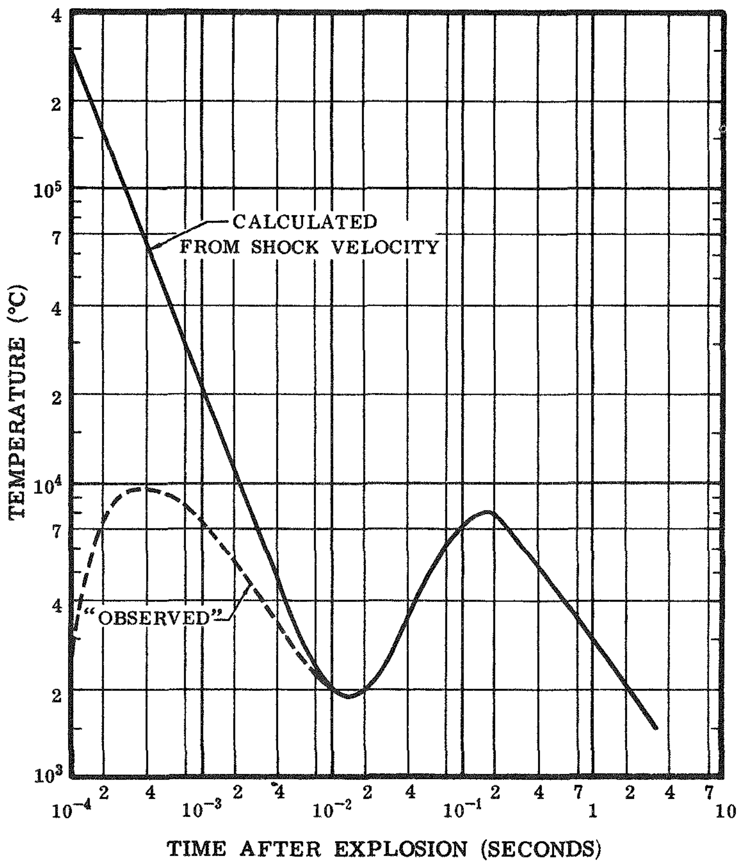

Figure 2.113. Variation of apparent fireball surface temperature with time in a 20-kiloton explosion.

2.114 As long as the temperature of the shock front is above a few thousand degrees, the air is opaque to the radiation from the isothermal sphere, and so the latter cannot be seen. The rate at which the shock front emits (and absorbs) radiation is determined by its temperature and radius. The temperature at this time is considerably lower than that of the isothermal sphere but the radius is larger. However, as the temperature of the shocked air approaches 1,800° C it absorbs (and radiates) less readily. Thus the shock front becomes increasingly transparent to the radiation from the isothermal sphere and there is a gradual unmasking of the still hot isothermal sphere, representing breakaway (§ 2.110).

2.115 As a result of this unmasking of the isothermal sphere, the apparent surface temperature of the fireball then increases (Fig. 2.113), after passing through the temperature minimum at about 1,800° C attributed to the shock front. This minimum, representing the end of the first thermal pulse, occurs at about 11 milliseconds (0.011 second) after the explosion time for a 20-kiloton weapon. Subsequently, as the apparent surface temperature continues to increase from the minimum, radiation from the fireball is emitted directly from the hot interior (or isothermal sphere), largely unimpeded by the cooled air in the shock wave ahead of it, so that energy is radiated more rapidly than before. The apparent surface temperature increases to a maximum of about 7,700° C (14,000° F), and this is followed by a steady decrease over a period of seconds as the fireball cools and ceases to radiate appreciably. It is during the second pulse that the major part of the thermal radiation is emitted in an air burst, the rate of emission being greatest when the surface temperature is at the maximum.

2.116 The curves in Figs. 2.111 and 2.113 apply to a 20-kiloton nuclear burst, but similar results are obtained for explosions of other energy yields. The rate of growth of the fireball depends on the actual yield, and so does the maximum radius. The time of thermal minimum increases with the energy yield, a good approximation for an air burst being given by the scaling law

$$t_{\min} \approx 0.0025\ W^{1/2},$$

where $t_{\min}$ is the time in seconds and W is in kilotons TNT equivalent. The observed breakaway time is slightly later than that of apparent surface temperature minimum for the same energy. The time at which the maximum temperature occurs in an air burst is related to the explosion energy, except perhaps for very high yields, by

$$t_{\max} \approx 0.032\ W^{1/2},$$

so that it is longer than the time to the minimum by a factor of more than ten. For contact surface bursts, the respective times are greater by 30 percent or so. It should be noted that, although the times vary with the energy yield, the respective minimum and maximum radiating surface temperatures are essentially independent of the explosion energy.

Size of Fireball

2.117 The size of the fireball increases with the energy yield of the explosion. Because of the complex interaction of hydrodynamic and radiation factors, the radius of the fireball at the thermal minimum is not very different for air and surface bursts of a given yield. The relationship between the average radius and the yield is then given approximately by

$$R \text{ (at thermal minimum)} \approx 90\ W^{0.4},$$

where R is the fireball radius in feet and W is the explosion yield in kilotons TNT equivalent. The breakaway phenomenon, on the other hand, is determined almost entirely by hydrodynamic considerations, so that a distinction should be made between air and surface bursts. For an air burst the radius of the fireball is given by

$$R \text{ (at breakaway) for air burst} \approx 110\ W^{0.4}. \qquad (2.117.1)$$

In the case of a contact surface burst, i.e., in which the exploding weapon is actually on the surface, blast wave energy is reflected back from the surface into the fireball (§ 2.33) and W in equation (2.117.1) should probably be replaced by $2W$, where W is the actual yield. Hence, for a contact surface burst,

$$R \text{ (at breakaway) for contact surface burst} \approx 145\ W^{0.4}. \qquad (2.117.2)$$

For surface bursts in the transition range between air bursts and contact bursts, the radius of the fireball at breakaway is somewhere between the values given by equations (2.117.1) and (2.117.2). The size of the fireball is not well defined in its later stages, but as a rough approximation the maximum radius may be taken to be about twice that at the time of breakaway (cf. Fig. 2.111).

2.118 Related to the fireball size is the question of the height of burst at which early (or local) fallout ceases to be a serious problem. As a guide, it may be stated that this is very roughly related to the weapon yield by

$$H \text{ (maximum for local fallout)} \approx 180\ W^{0.4}, \qquad (2.118.1)$$

where H feet is the maximum value of the height of burst for which there will be appreciable local fallout. This expression is plotted in Fig. 2.118. For an explosion of 1,000 kilotons, i.e., 1 megaton yield, it can be found from Fig. 2.118 or equation (2.118.1) that significant local fallout is probable for heights of burst less than about 2,900 feet. It should be emphasized that the heights of burst estimated in this manner are approximations only, with probable errors of ± 30 percent. Furthermore, it must not be assumed that if the burst height exceeds the value given by equation (2.118.1) there will definitely be no local fallout. The amount, if any, may be expected, however, to be small enough to be tolerable under emergency conditions.

High-Altitude Bursts

2.119 For nuclear detonations at heights up to about 100,000 feet, the density of air is such that the distribution of the explosion energy remains almost unchanged, approximating that described in § 1.22, e.g., about 45 to 55 percent (of the fission energy) appears as blast and shock and 30 to 40 percent is received as thermal radiation. At greater altitudes, this distribution begins to change noticeably with increasing height of burst, a smaller proportion of the energy appearing as blast. It is for this reason that the level of 100,000 feet has been chosen for distinguishing between air bursts and high-altitude bursts. There is, of course, no sharp change in behavior at this elevation, and so the definition of a high-altitude burst as being at a height above 100,000 feet is somewhat arbitrary. Although there is a progressive decline in the blast energy with increasing height of burst above 100,000 feet, the proportion of the explosion energy received as effective thermal radiation on the ground does not at first change appreciably. This is due to the interaction of the primary thermal radiation with the surrounding air and its subsequent emission in a different spectral region, as explained below. At still higher altitudes, the effective thermal radiation received on the ground decreases and is, in fact, less than at an equal distance from an air burst of the same total yield (§ 7.25).

2.120 When a nuclear explosion occurs at a very high altitude, the low density of the air affects the development of the fireball phenomena in several ways. The probability of interaction of the primary thermal radiation, i.e., the thermal X-rays, with atoms and molecules in the air is markedly decreased, so that the photons have long mean free paths and travel greater distances, on the average, before they are absorbed or degraded into a different form of energy. The volume of the atmosphere in which the energy of the radiation is deposited,

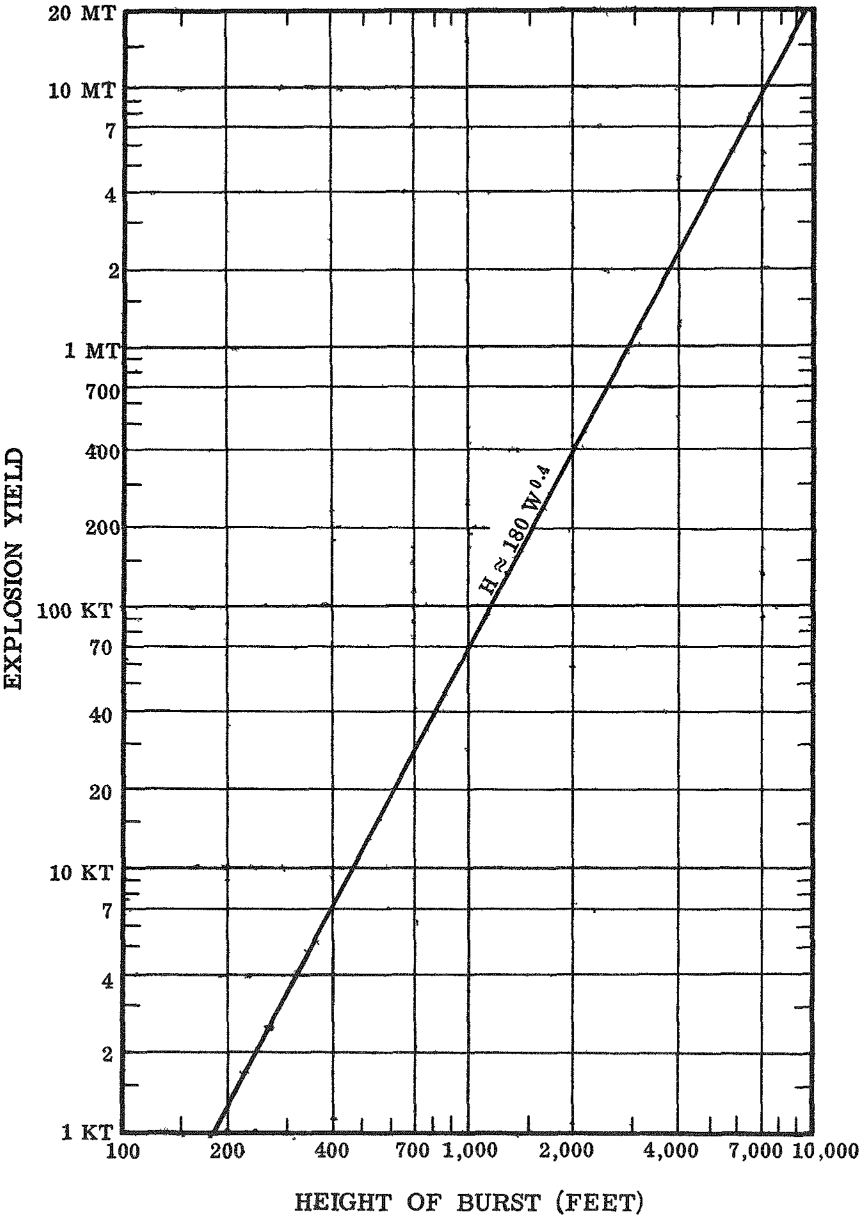

Figure 2.118. Approximate maximum height of burst for appreciable local fallout.

over a period of a millisecond or so, may extend for many miles, the dimensions increasing with the altitude burst. The first interaction of the X-rays with the air is to produce a strong flash of light, called

"flourescence radiation," lasting perhaps a microsecond, This light, which is intense in the ultraviolet and visible regions, is similar to that observed in electrical discharges through air in the laboratory; it consists predominantly of emission from excited neutral and ionized molecules of nitrogen.

2.121 Most of the X-ray energy is absorbed in the large volume of air which has a considerable mass, in spite of its low density. Consequently, the fireball temperatures, although of the order of 10,000° C (18,000° F) or more, are much lower than for an explosion at sea-level densities. Various excited atoms and ions are formed in the air, as a result of interaction with the thermal X-rays, and the radiation re-emitted by these species represents the thermal radiation observed at a distance. About half of the absorbed energy is emitted in this manner in less than a second from a megaton-range explosion at an altitude of about 250,000 feet and constitutes the main pulse of thermal radiation. The remainder of the thermal energy is radiated so slowly that it can be ignored as a significant effect.

2.122 A qualitative comparison of the rate of arrival of thermal radiation energy at a distance from the burst point as a function of time for a megaton-range explosion at high altitude and in a sea-level atmosphere is shown in Fig. 2.122. It is seen, as mentioned above, that in the high-altitude burst there is only a single pulse of relatively short duration. Not only is the pulse shorter and more intense than in a normal air burst, but it is richer in ultraviolet radiation. This is because of the decreased formation of ozone, oxides of nitrogen, and nitrous acid (§ 2.113) which absorb strongly in this spectral region.

2.123 Because the primary thermal radiation energy in a high-altitude burst is deposited in a much larger volume of air, the energy per unit volume available for the development of the shock front is less than in an air burst. Furthermore, the shock wave is slow to form, so that in the meantime the fireball radiates a large fraction of its energy. Consequently the shock front does not become hot enough to be opaque at times sufficiently early to mask the radiation front and cause an apparent temperature minimum as in the case of an air burst. Thus, with increasing height, a series of changes take place in the thermal pulse phenomena; the surface temperature minimum becomes less pronounced and eventually disappears, so that the thermal radiation is emitted in a single pulse. It is for this reason that the TEAK high-altitude shot was accompanied by a single bright flash of light of short duration (§ 2.56).

2.124 Although the energy density in the atmosphere as the result of a high-altitude burst is small compared with that from an air burst of the same yield, a shock wave is ultimately produced in the

upper atmosphere. For example, disturbance of the ionosphere in the vicinity of Hawaii after the TEAK shot indicated that a shock wave was being propagated at that time at an average speed of about 4,200 feet per second. The formation of the large red, luminous sphere, several hundred miles in diameter, surrounding the fireball, has been attributed to the electronic excitation of oxygen atoms by the energy of the blast wave. Soon after excitation, the excess energy is emitted as visible radiation toward the red end of the spectrum (6,300 and 6,364 A).

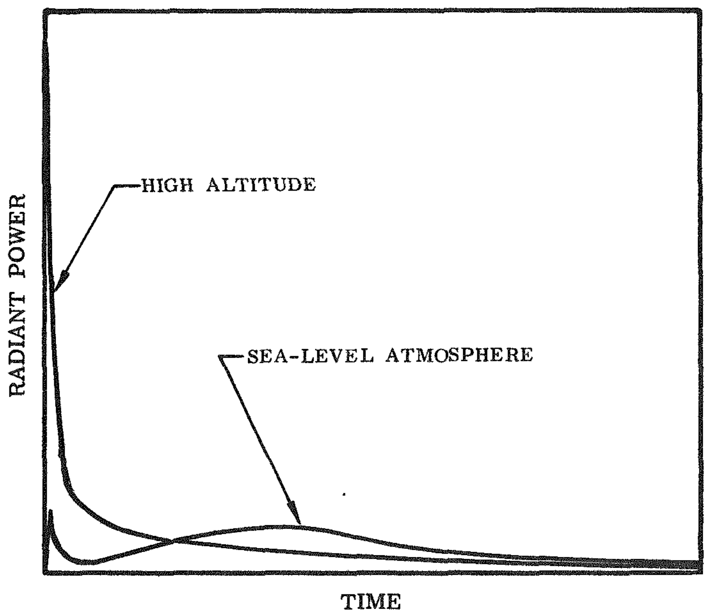

Figure 2.122. Qualitative comparison of rates of arrival of thermal radiation at a given distance from high-altitude and sea-level bursts.

2.125 The formation of auroras and the disturbances in the ionosphere which affect the transmission of radio (and similar) waves are caused by electrically charged particles produced directly or indirectly as a result of the nuclear explosion. It is well known that the ionosphere, which is that part of the atmosphere above an altitude of about 40 miles, plays an important part in the propagation of certain radio waves over long distances. The ability of the ionosphere to reflect these waves is dependent upon normal variations in the electron density at different levels. The neutrons and gamma rays present in the initial nuclear radiation and the beta particles

and gamma rays from the fission residues, as well as the thermal X-rays, are capable of producing ionization, i.e., forming ions and electrons, by interaction with the oxygen and nitrogen in the atmosphere. Hence, a nuclear explosion is accompanied by a large increase in the electron density (or concentration). In the event of an air burst at moderate altitude, the electrons are promptly removed by attachment to neutral molecules or by recombination with ions; consequently, although radio signals in the immediate vicinity of the explosion will be affected, there will be little interference with radio communications in general. For a burst at high altitudes, however, the electrons can remain free for a longer time in the low-density air, thus causing a significant disturbance of the normal ionospheric electron densities. As a result there may be a "black-out" of radio signals over a large area for several hours. In some circumstances the earth's magnetic field contributes to the situation, as will be described below.

2.126 The auroral effects associated with high-altitude nuclear explosions are primarily due to the beta particles emitted by the fission products when they undergo radioactive decay. The earth's magnetic field exerts forces on charged particles so that they are largely constrained to travel in helical (spiral) paths along the field lines. When the beta particles formed in a nuclear detonation and trapped in this manner enter the upper atmosphere, they cause electronic excitation (and ionization) of the atoms and molecules in the air. The excess energy is then re-emitted as visible radiation characteristic of the aurora.

2.127 The remote auroras, such as those observed at Apia following the TEAK and ORANGE shots, arise from the fact that the earth behaves like a magnetic dipole, i.e., it has two (one north and one south) poles. Hence every line of force reaches the earth at two points, called "conjugate points," one north of the magnetic equator and the other south of it. For the lines of force passing through the TEAK and ORANGE points of burst, the near conjugate point, in the northern hemisphere, is somewhat to the northeast of Johnston Island whereas the more remote conjugate point, in the southern hemisphere, is to the northwest of Apia. Hence, the charged particles spiraling about the earth's magnetic lines of force will enter the atmosphere near these two locations and these are where the auroras may be expected to form (Fig. 2.127). Since it takes a very short time—no more than a fraction of a second—for the beta particles to travel along the field lines from the point of burst to the southern conjugate point, the aurora was seen at Apia at almost the same time as that observed from Johnston Island.

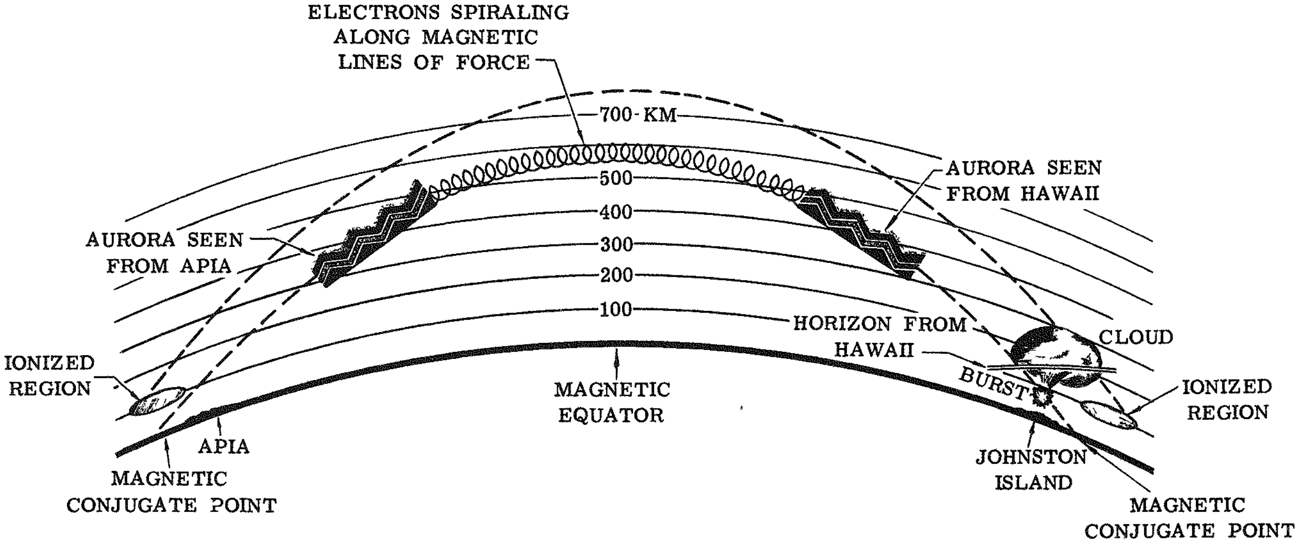

Figure 2.127. Phenomena associated with high-altitude explosions.

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2.128 For bursts at sufficiently high altitudes, the fission product ions move along the earth's lines of force and are mostly brought to rest at altitudes of about 70 miles near the conjugate points. There they continue to decay and so act as a stationary source of beta particles. On the other hand, the neutral fission products remaining in the vicinity of the burst point emit beta particles which travel toward the conjugate points along the lines of force. However, when they enter a region where the strength of the earth's magnetic field increases, as it does near the conjugate points, a small proportion of the beta particles are turned back (or reflected), so that they travel back and forth a number of times before they are eventually captured.

2.129 In actual fact, the interactions of the ionized and neutral particles and radiations from a nuclear explosion with the earth's magnetic field and with the atmosphere are more complicated than outlined above. For example, in addition to the motion of the charged particles along the field lines, there is a tendency for them to move across the lines wherever the magnetic field strength is not uniform. This results in an eastward (longitudinal) drift around the earth superimposed on the back and forth spiral motion between regions near the conjugate points. Furthermore, the general behavior is strongly affected by the altitude at which the nuclear burst occurs. These and other related matters are discussed more fully in Chapter X.

Nuclear Explosions and the Weather

2.130 There has been speculation, from time to time, especially after a series of test detonations in the Pacific or in Nevada, concerning the possible influence of nuclear explosions on the weather. This speculation is based primarily on two considerations. First, it was thought that the energy added to the atmosphere by the explosions might change the existing weather pattern, and second, that the products of the explosion might serve as a trigger to divert some much larger natural store of energy from the path it might otherwise have followed.

2.131 The addition of energy to the atmosphere does not appear to be an important factor since the amount of energy released in a nuclear explosion is not large in comparison with that associated with most meteorological phenomena. Furthermore, it is not produced in a manner that is likely to be conducive to weather changes. There is a possibility that the atmosphere may be in an unstable state, and so the sudden impulse of a nuclear explosion might cause a change in the weather that would otherwise not take place. As

far as thunderstorm formation is concerned, it is believed that the release of energy in a nuclear explosion is so rapid that the atmospheric conditions could not be rearranged within the limited time to take advantage of the extra energy.

2.132 There are three ways, which appear reasonable, whereby the products of a nuclear explosion might indirectly, e.g., by trigger action, produce changes in the weather. These are (1) the debris thrown into the air by the explosion may have an effect in seeding (nucleating) existing clouds, thus changing the pattern of cloudiness or precipitation over large areas; (2) the radioactive nature of the weapon residues will change the electrical conductivity of the air and this may have an influence on observable meteorological phenomena; and (3) the debris entering the stratosphere may interfere with the transmission of radiant energy from the sun and so serve to decrease the temperature of the earth. These possibilities will be considered in turn.

2.133 Although the techniques for testing seeding efficiency are not too well developed and are being given further study, the evidence obtained so far indicates that weapon debris is not effective as a cloud-seeding agent. It is true that rain fell after the nuclear explosion over Hiroshima in August 1945, but it seems certain that this was largely, if indirectly, due to widespread fires which sustained convection for several hours after the detonation had occurred. A similar phenomenon has been observed, under suitable air mass conditions, as a result of a "fire storm" over large forest fires and over burning cities during World War II. However, there has been no analogous effect in connection with the numerous test explosions of nuclear devices, since these were not accompanied by large fires.

2.134 Within two or three hours after the Bikini ABLE (air) burst in 1946, light rain showers developed throughout the northern Marshall Islands. Some attempt was made to relate the formation of the showers to the radioactive cloud. But the showers were very widespread and were readily explained on the basis of the existing meteorological conditions. The records show that the only detectable changes which occurred in the wind or atmospheric structure were the momentary effects of the blast and thermal radiation. In any event, such changes were significant only in the immediate vicinity of the burst. The main cloud pattern over the lagoon was unchanged apart from the radioactive cloud directly associated with the explosion.

2.135 The amount of ionization produced by the radioactive material, even for a high-energy nuclear explosion, is believed to be insufficient to cause any significant disturbance of general atmospheric

conditions. It appears improbable, therefore, that the ionization accompanying a nuclear explosion can affect the weather, although it may produce auroral effects and interfere with radio transmission.

2.136 The dust raised in severe volcanic eruptions, such as that at Krakatoa in 1883, is known to cause a noticeable reduction in the sunlight reaching the earth, but it has not been established that this decrease has any great effect on the weather. The amount of debris remaining in the atmosphere after the explosion of even the largest nuclear weapons is probably not more than about 1 percent or so of that raised by the Krakatoa eruption. Moreover, solar radiation records reveal that none of the nuclear explosions to date has resulted in any detectable change in the direct sunlight recorded on the ground.

2.137 The variability of weather phenomena due to natural causes makes it difficult to prove (or disprove) that any change in the weather following a nuclear explosion was due to the detonation. However, the general opinion of competent meteorologists, both in the United States and in other countries, is that, apart from localized effects in the vicinity of the test area, there has been no known influence of nuclear explosions on the weather.

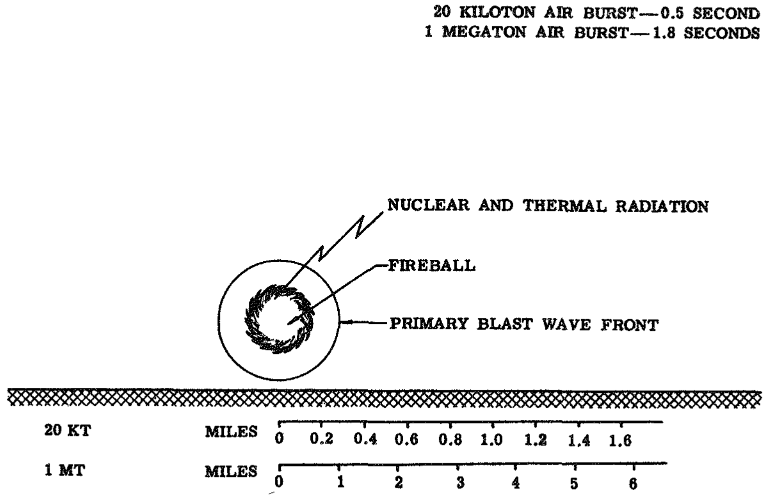

Figure 2.51a. Chronological development of an air burst; 0.5 second after 20-kiloton detonation; 1.8 seconds after 1-megaton detonation.

CHRONOLOGICAL DEVELOPMENT OF AIR BURST

Immediately following the detonation of a nuclear weapon in the air, an intensely hot and luminous (gaseous) fireball is formed. Because of its extremely high temperature, it emits thermal (or heat) radiation capable of causing skin burns and starting fires in flammable material at a considerable distance. The nuclear processes which cause the explosion and the radioactive decay of the fission products are accompanied by harmful nuclear radiations (gamma rays and neutrons) which also have a long range in air. Very soon after the explosion, a destructive shock (or blast) wave develops in the air and moves rapidly away from the fireball.

At the times indicated, the fireball has almost attained its maximum size, as shown by the figures given below:

	Diameter of fireball (feet)	
	20 kilotons	*1 megaton*
At time indicated	1, 460	6, 300
Maximum	1, 550	7, 200

The blast wave front in the air is seen to be well ahead of the fireball, about 800 feet for the 20-kiloton explosion and roughly half a mile for the 1-megaton detonation.

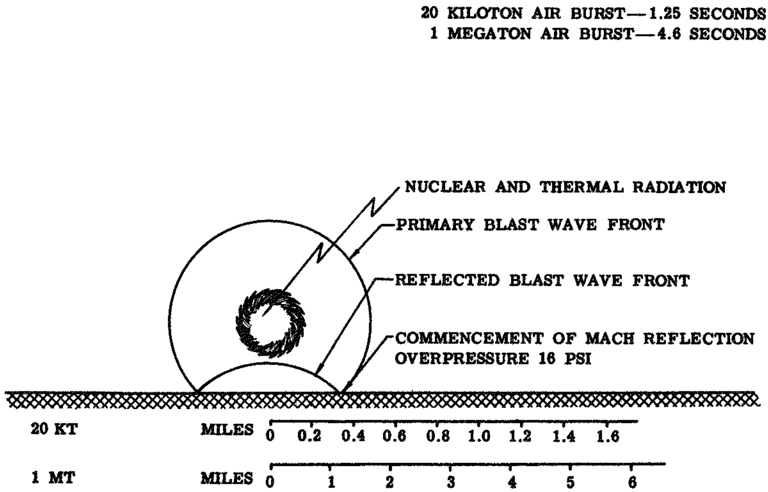

Figure 2.51b. Chronological development of an air burst; 1.25 seconds after 20-kiloton detonation; 4.6 seconds after 1-megaton detonation.

When the primary air blast wave from the explosion strikes the ground, another blast wave is produced by reflection. At a certain distance from ground zero, which depends upon the height of burst and the energy yield of the weapon, the primary and reflected wave fronts fuse near the ground to form a single, reinforced Mach front (or stem).

The time and distance at which the Mach effect commences for the air bursts at the given heights are as follows:

Explosion yield	*Height of burst (feet)*	*Time after detonation (seconds)*	*Distance from ground zero (miles)*
20 kilotons	1, 760	1. 25	0. 35
1 megaton	6, 500	4. 6	1. 3

The overpressure at the earth's surface is then 16 pounds per square inch.

Significant quantities of thermal and nuclear radiations continue to be emitted from the fireball.

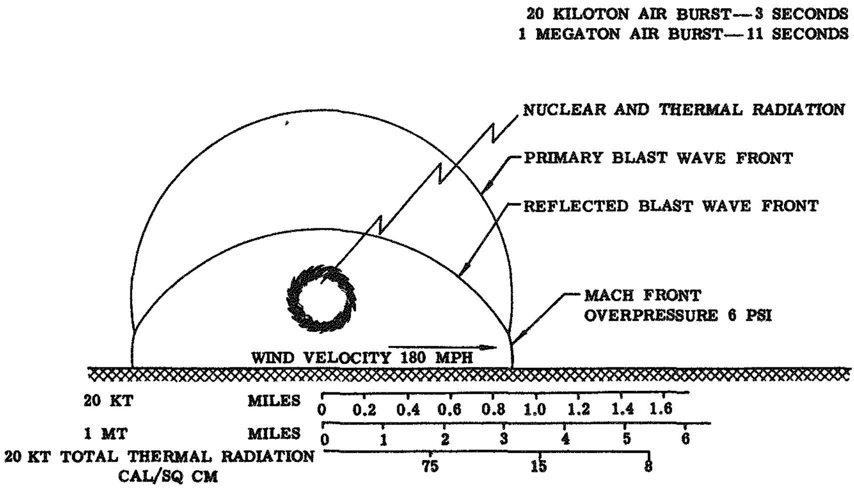

Figure 2.51c. Chronological development of an air burst; 3 seconds after 20-kiloton detonation; 11 seconds after 1-megaton detonation.

As time progresses, the Mach front (or stem) moves outward and increases in height. The distance from ground zero and the height of the stem at the times indicated are as follows:

Explosion yield	*Height of burst (feet)*	*Time after detonation (seconds)*	*Distance from ground zero (miles)*	*Height of stem (feet)*
20 kilotons	1, 760	3	0. 87	185
1 megaton	6, 500	11	3. 2	680

The overpressure at the Mach front is 6 pounds per square inch and the blast wind velocity immediately behind the front is about 180 miles per hour.

Nuclear radiations from the weapon residues in the rising fireball continue to reach the ground. But after 3 seconds from the detonation of a 20-kiloton weapon, the fireball, although still very hot, has cooled to such an extent that the thermal radiation is no longer important. The total accumulated amounts of thermal radiation, expressed in calories per square centimeter, received at various distances from ground zero after a 20-kiloton air burst, at 1,760 feet, are shown on the scale at the bottom of the figure (for further details, see Chapter VII). Appreciable amounts of thermal radiation are still received from the fireball at 11 seconds after a 1-megaton explosion; the thermal radiation emission is spread over a longer time interval than for an explosion of lower energy yield.

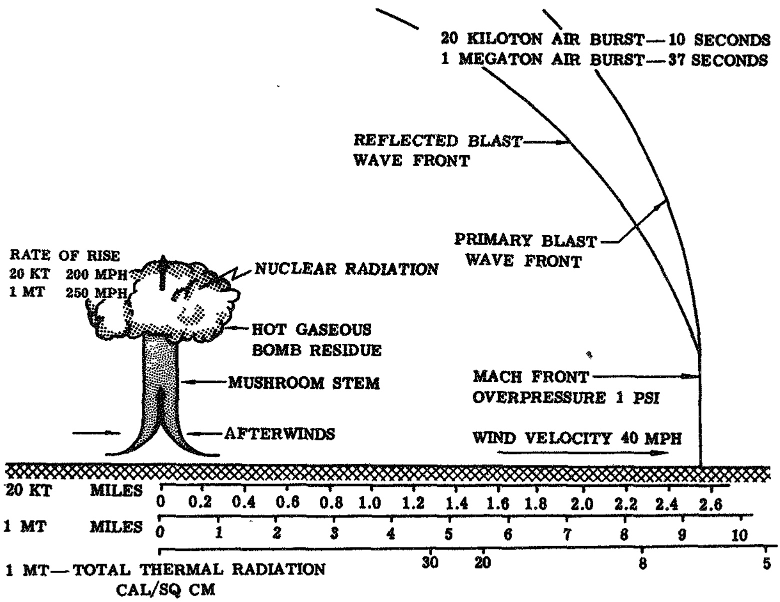

Figure 2.51d. Chronological development of an air burst; 10 seconds after 20-kiloton detonation; 37 seconds after 1-megaton detonation.

At 10 seconds after a 20-kiloton explosion at an altitude of 1,760 feet the Mach front is over 2½ miles from ground zero, and 37 seconds after a 1-megaton detonation at 6,500 feet, it is nearly 9½ miles from ground zero. The overpressure at the front is roughly 1 pound per square inch, in both cases, and the wind velocity behind the front is 40 miles per hour. There will be slight damage to many structures, including doors and window frames ripped off, roofs cracked, and plaster damaged. Glass will be broken at overpressures down to ½ pound per square inch. Thermal radiation is no longer important, even for the 1-megaton burst, the total accumulated amounts of this radiation, at various distances, being indicated on the scale at the bottom of the figure. Nuclear radiation, however, can still reach the ground to an appreciable extent; this consists mainly of gamma rays from the fission products.

The fireball is no longer luminous, but it is still very hot and it behaves like a hot-air balloon, rising at a rapid rate. As it ascends, it causes air to be drawn inward and upward, somewhat similar to the updraft of a chimney. This produces strong air currents, called afterwinds. For moderately low air bursts, these winds will raise dirt and debris from the earth's surface to form the stem of what will eventually be the characteristic mushroom cloud.

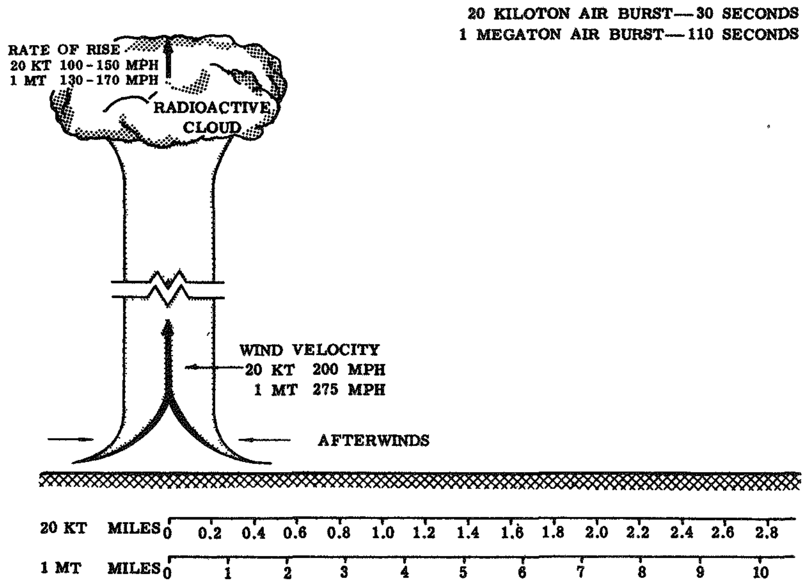

Figure 2.51e. Chronological development of an air burst; 30 seconds after 20-kiloton detonation; 110 seconds after 1-megaton detonation.

The hot residue of the weapon continues to rise and at the same time it expands and cools. As a result, the vaporized fission products and other weapon residues condense to form a cloud of highly radioactive particles. The afterwinds have velocities of 200 or more miles per hour, and for a sufficiently low burst they will continue to raise a column of dirt and debris which will later join with the radioactive cloud to form the characteristic mushroom shape. At the times indicated, the cloud from a 20-kiloton explosion will have risen about 1½ miles and that from a 1-megaton explosion about 7 miles. After about 10 minutes, the maximum heights attained by the clouds will be about 7 miles and 14 miles, respectively. Ultimately, the particles in the cloud will be dispersed by the wind and, unless there is precipitation, there will usually be no early (or local) fallout. Only if the height of burst is less than about 600 feet for a 20-kiloton and 3,000 feet for a 1-megaton explosion would appreciable early fallout be expected.

Although the cloud is still highly radioactive, very little of the nuclear radiation reaches the ground. This is the case because of the increased distance of the cloud above the earth's surface and the decrease in the activity of the fission products due to natural radioactive decay.

100 KILOTON SHALLOW UNDERWATER BURST—2 SECONDS

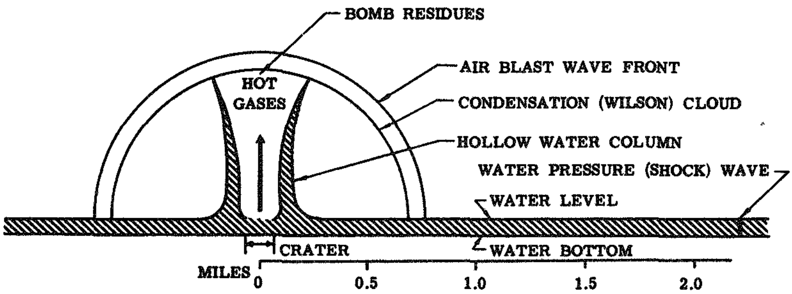

Figure 2.80a. Chronological development of a 100-kiloton shallow underwater burst: 2 seconds after detonation.

CHRONOLOGICAL DEVELOPMENT OF SHALLOW UNDERWATER BURST

When a nuclear weapon is exploded under the surface of water, a bubble of intensely hot gases and steam is formed which will burst through the surface if the detonation occurs at a shallow depth. As a result, a hollow column of water and spray is shot upward, reaching a height of over 5,000 feet in 2 seconds after a 100-kiloton explosion. The gaseous weapon residues are then vented through the hollow central portion of the water column.

The shock (or pressure) wave produced in the water by the explosion travels outward at high speed, so that at the end of 2 seconds it is more than 2 miles from surface zero. The expansion of the hot gas and steam bubble also results in the formation of a shock (or blast) wave in the air, but this moves less rapidly than the shock wave in water, so that the front is some 0.8 mile from surface zero.

Soon after the air blast wave has passed, a dome-shaped cloud of condensed water droplets, called the condensation cloud, may form for a second or two. Although this phenomenon is impressive, it has apparently no significance as far as nuclear attack or defense is concerned.

For an underwater burst at moderate (or great) depth, essentially all of the thermal radiation and much of the initial nuclear radiation is absorbed by the water.

100 KILOTON SHALLOW UNDERWATER BURST—12 SECONDS

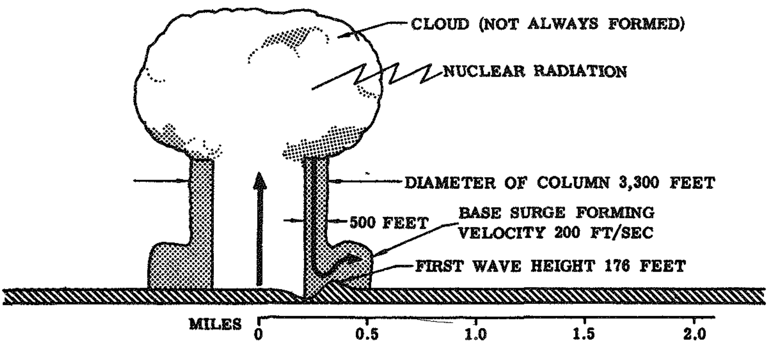

Figure 2.80b. Chronological development of a 100-kiloton shallow underwater burst: 12 seconds after detonation.

At 12 seconds after the 100-kiloton explosion, the diameter of the water column is about 3,300 feet, and its walls are some 500 feet thick. The weapon residues venting through the hollow central portion condense and spread out to form the cauliflower-shaped cloud, partly obscuring the top of the column. The cloud is highly radioactive, due to the presence of fission products, and hence it emits nuclear radiations. Because of the height of the cloud these radiations are a minor hazard to persons near the surface of the water.

At 10 to 12 seconds after a shallow underwater explosion, the water falling back from the column reaches the surface and produces around the base of the column a ring of highly radioactive mist, called the base surge. This ring-shaped cloud moves outward, parallel to the water surface, at high speed, initially 200 feet per second (135 miles per hour). For underwater bursts at certain depths, the radioactive cloud may not be formed, although there will generally be a base surge.

The disturbance due to the underwater explosion causes large water waves to form on the surface. At 12 seconds after a 100-kiloton explosion, the first of these is about 1,800 feet (0.34 mile) from surface zero, and its height, from crest to trough, is 176 feet.

100 KILOTON SHALLOW UNDERWATER BURST—20 SECONDS

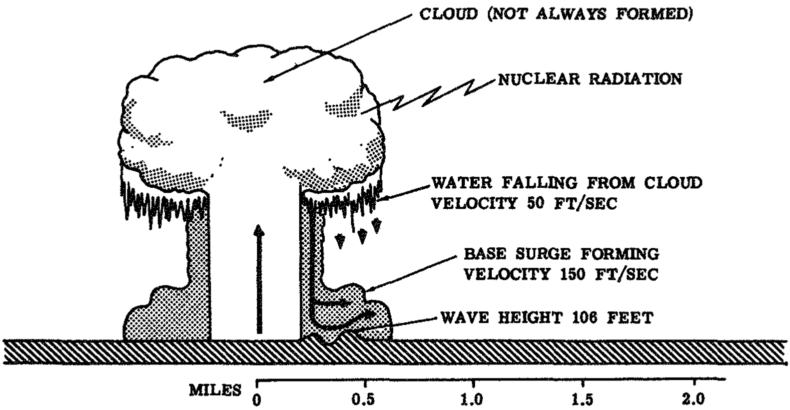

Figure 2.80c. Chronological development of a 100-kiloton shallow underwater burst: 20 seconds after detonation.

As the water and spray forming the column continue to descend, the base surge cloud develops, billowing upward and moving outward across the surface of the water. At 20 seconds after the 100-kiloton explosion the height of the base surge is about 1,000 feet and its front is nearly ½ mile from surface zero. It is then progressing outward at a rate of approximately 150 feet per second (100 miles per hour).

At about this time, large quantities of water, sometimes referred to as the massive water fallout, begin to descend from the radioactive cloud, if it is formed. The initial rate of fall is about 50 feet per second. The diameter of the column has now decreased to 2,000 feet.

By the end of 20 seconds, the first water wave has reached about 2,000 feet (0.38 mile) from surface zero and its height is roughly 106 feet.

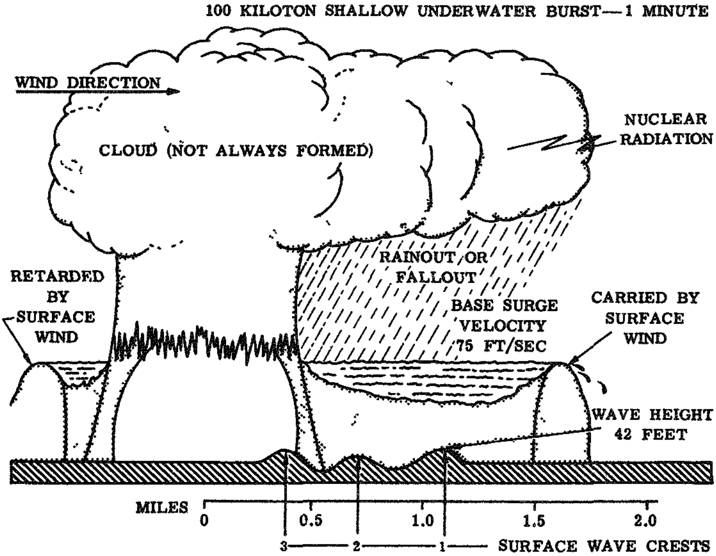

Figure 2.80d. Chronological development of a 100-kiloton shallow underwater burst: 1 minute after detonation.

At 1 minute after the underwater burst, the water falling from the radioactive cloud reaches the surface, forming a region of primary cloud fallout. There is consequently a continuous ring of water and spray between the cloud, if one has formed, and the surface of the water.

At about this time, the base surge has become detached from the bottom of the column, so that its ring-like character is apparent. The height of the base surge cloud is now 1,300 feet and its front, moving outward at some 75 feet per second (50 miles per hour), is about 1.2 miles from surface zero. Because of the radioactivity present in the base surge, the latter represents a hazard to personnel.

Several water waves have now developed, the first, with a height of 42 feet, being approximately 1 mile from surface zero.

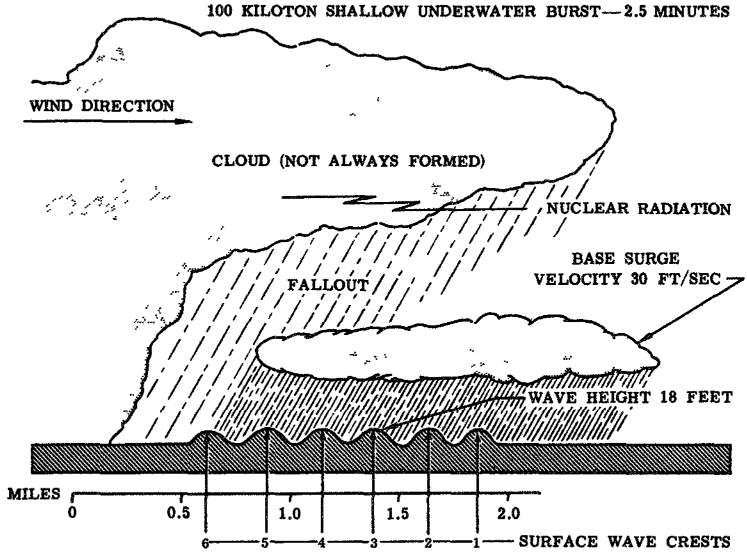

Figure 2.80e. Chronological development of a 100-klloton shallow underwater burst: 2.5 minutes after detonation.

By 2½ minutes after the 100-kiloton underwater explosion, the front of the base surge is nearly 2 miles from ground zero and its height is roughly 2,000 feet. The effective spread of the visible base surge cloud at 4 minutes is approximately 2½ miles from surface zero, i.e., 5 miles across. The base surge now appears to be rising from the surface of the water. This effect is attributed to several factors, including an actual increase in altitude, thinning of the cloud by engulfing air, and raining out of the larger drops of water. Due to natural radioactive decay of the fission products, to rainout, and to dilution of the mist by air, the intensity of the nuclear radiation from the base surge at 2½ minutes after the explosion is only one-twentieth of that at 1 minute.

The descent of water and spray from the column and from condensation in the radioactive cloud results in the formation of a continuous mass of mist or cloud down to the surface of the water. Ultimately, this merges with the base surge, which has spread and increased in height, and also with the natural clouds of the sky, to be finally dispersed by the wind.

After 4 or 5 minutes, the visible base surge will begin to disappear as the water droplets evaporate. However, radioactive particles will still be present and will spread out in the form of the invisible base surge.

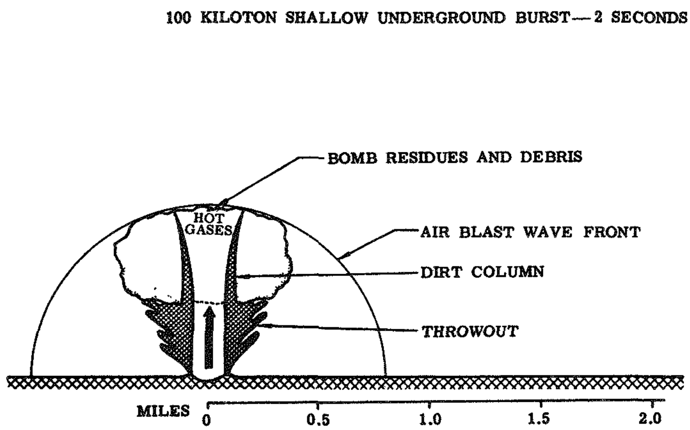

Figure 2.93a. Chronological development of a 100-kiloton shallow underground burst: 2.0 seconds after detonation.

CHRONOLOGICAL DEVELOPMENT OF UNDERGROUND BURST

When a nuclear explosion occurs at a shallow depth underground, the fireball breaks through the surface of the earth within a fraction of a second of the instant of detonation. The intensely hot gases at high pressure are released and they carry up with them into the air large quantities of soil, rock, and debris in the form of a hollow column. For a burst at a shallow depth, the column tends to assume the shape of an inverted cone which fans out as it rises to produce a radial throw-out. A highly radioactive cloud, which contains large quantities of earth, is formed above the throw-out as the hot vapors cool and condense. Because of the mass displacement of material from the earth's surface, a crater is formed. For a 100-kiloton weapon exploding 50 feet beneath the surface of dry soil, the crater would be about 120 feet deep and 720 feet across. The weight of the material removed would be over a million tons.

In addition to the shock (or pressure) wave in the ground, somewhat related to an earthquake wave, the explosion is accompanied by a blast wave in the air. At 2 seconds after the explosion, the blast wave front in air is about ¾ mile from surface zero.

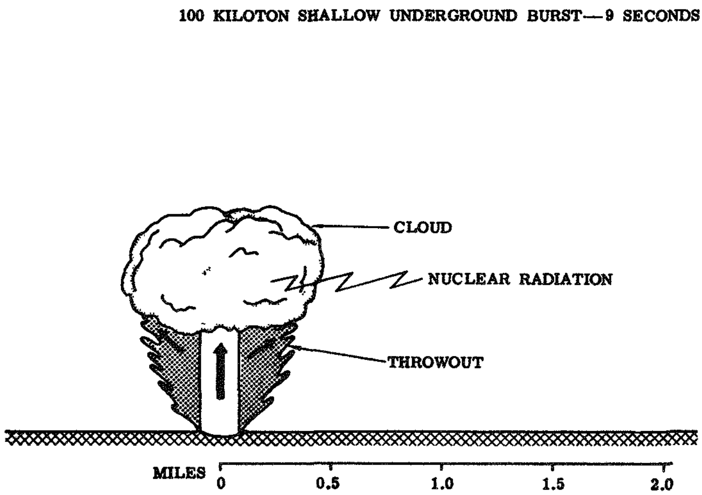

Figure 2.93b. Chronological development of a 100-kiloton shallow underground burst: 9.0 seconds after detonation.

The radioactive cloud continues to rise, giving off intense nuclear radiations which are still a hazard on the ground at 9 seconds after the detonation. At this time, the larger pieces of rock and debris in the throw-out begin to descend to earth.

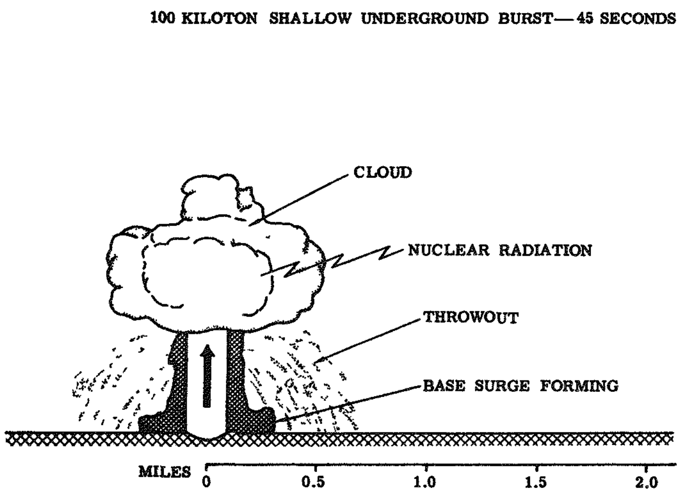

Figure 2 93c Chronological development of a 100-kiloton shallow underground burst: 45 seconds after detonation.

As the material from the column descends, the finer soil particles attain a high velocity and upon reaching the ground they spread out rapidly to form a base surge similar to that in an underwater explosion. The extent of the base surge, which is likely to be radioactive, depends upon many factors, including the energy yield of the explosion, the depth of burst, and the nature of the soil. It is believed that a dry sandy terrain would be particularly conducive to base surge formation.

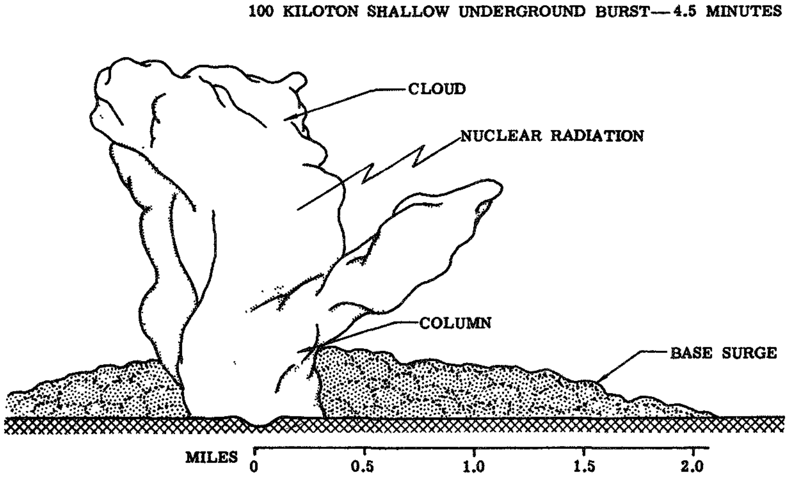

Figure 2.93d. Chronological development of a 100-kiloton shallow underground burst: 4.5 minutes after detonation.

The base surge increases in height and area and soon begins to merge with the radioactive cloud of weapon residues, etc., part of which descends and spreads out under the influence of the prevailing winds. In due course, the radioactive clouds disperse, but the contaminated particles descend to earth to produce a hazardous fallout over a large area, especially in the downwind direction, during the course of a few hours.

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*These documents may be obtained for a small charge from Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C.

3.11 The dynamic pressure is proportional to the square of the wind velocity and to the density of the air behind the shock front. Both of these quantities may be related to the overpressure under ideal conditions at the wave front by certain equations, which will be given later (see § 3.49). For very strong shocks the dynamic pressure is larger than the overpressure, but below 70 pounds per square inch overpressure at sea level the dynamic pressure is smaller. Like the peak shock overpressure, the peak dynamic pressure decreases with increasing distance from the explosion center, although at a different rate. Some indication of the corresponding values of peak overpressure, peak dynamic pressure, and maximum blast wind velocities for an ideal shock front in air at sea level are given in Table 3.11.

TABLE 3.11

OVERPRESSURE, DYNAMIC PRESSURE, AND WIND VELOCITY IN AIR AT SEA LEVEL FOR AN IDEAL SHOCK FRONT

Peak overpressure (pounds per square inch)	*Peak dynamic pressure (pounds per square inch)*	*Maximum wind velocity (miles per hour)*
200	330	2, 080
150	223	1, 778
100	123	1, 414
72	80	1, 170
50	40	940
30	16	670
20	8	470
10	2	290
5	0. 7	160
2	0. 1	70

3.12 At a given location, the dynamic pressure changes with time in a manner somewhat similar to the change in the overpressure, but the rate of pressure decrease behind the shock front is usually different. This may be seen from Fig. 3.12 which indicates how the two pressures vary in the course of the first few seconds or so following arrival of the shock front. In the case illustrated, the peak overpressure is about 5 pounds per square inch, so that the peak dynamic pressure is close to 0.7 pound per square inch; at different values of the peak overpressure the relative positions of the two curves will, of course, be different, in accordance with the data in Table 3.11.

3.13 When the shock front reaches the given point, both the overpressure and the dynamic pressure increase almost immediately from zero to their maximum values and then decrease. The dynamic pressure (and wind velocity) will fall to zero somewhat later than the

overpressure because of the momentum of the air in motion behind the shock front, but for purposes of estimating damage the difference is not significant. During the negative (or underpressure) phase of the blast wave the dynamic pressure is very small and acts in the opposite direction. Therefore, dynamic pressure (or drag force) damage sustained during the negative phase is generally small compared to that in the positive phase.

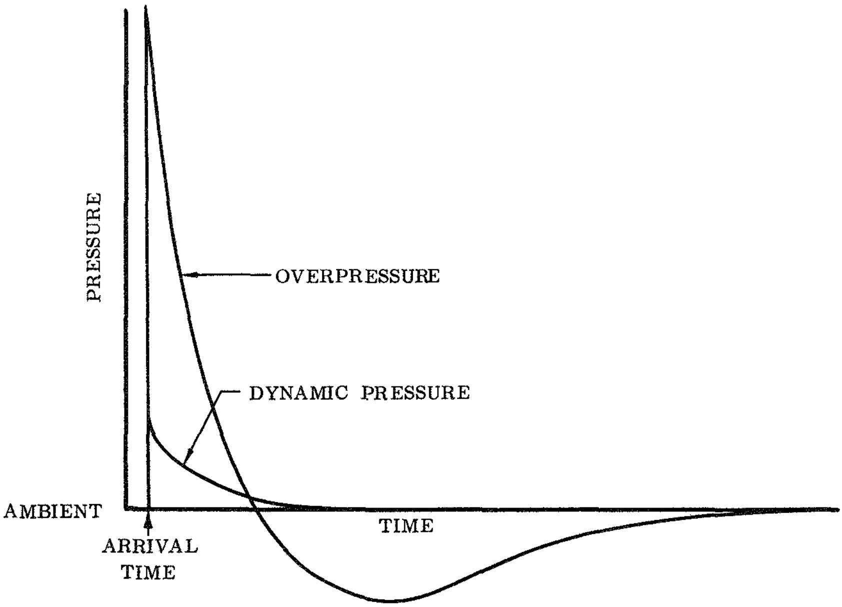


Figure 3.12. Variation of overpressure and dynamic pressure with time at a fixed location in the low-pressure region.

Arrival Time and Duration

3.14 As stated previously, there is a finite time interval required for the blast wave to move out from the explosion center to any particular location. This time interval (or arrival time) is dependent upon the energy yield of the explosion and the distance involved; at 1 mile from a 1-megaton burst, the arrival time would be about 4 seconds. Initially, the velocity of the shock front is quite high, many times the speed of sound, but as the blast wave progresses outward, it slows down as the pressure at the front weakens. Finally, at long ranges, the blast wave becomes essentially a sound wave and its velocity approaches ambient sound velocity.

3.15 The duration of the blast wave at a particular location also depends on the energy of the explosion and the distance from the point of burst. The positive phase duration is shortest at close ranges and increases as the blast wave moves outward. At 1 mile from a 1-megaton explosion, for example, the duration of the positive phase of the blast wave is about 2 seconds. There is a minimum positive duration associated with blast wave development which occurs prior to the formation of a negative phase.

3.16 It was noted above that the transient wind velocity decays to zero at a somewhat later time than the end of the overpressure positive phase. Consequently, the duration of the positive dynamic pressure phase may exceed that of the positive overpressure phase by varying amounts depending on the pressure level involved. However, positive dynamic pressures existing after the overpressure positive phase has ended are so low that they can be disregarded. Therefore the period of time over which the positive dynamic pressure is effective may be taken as essentially the positive phase duration of the overpressure. The same considerations apply to the respective negative phases.

REFLECTION OF BLAST WAVE AT A SURFACE

Incident and Reflected Waves

3.17 When the incident blast wave from an explosion in air strikes a more dense medium such as the earth's surface, e.g., either land or water, it is reflected. The formation of the reflected wave in these circumstances is represented in Fig. 3.17. This figure shows four stages in the outward motion of the spherical blast originating from an air burst. In the first stage the wave front has not reached the ground; the second stage is somewhat later in time, and in the third stage, which is still later, a reflected wave, indicated by the dotted line, has been produced.

3.18 When such reflection occurs, an individual or object precisely at the surface will experience a single pressure increase, since the reflected wave is formed instantaneously. Consequently, the value of the overpressure thus experienced at the surface is generally considered to be entirely a reflected pressure. In the region near ground zero, this total reflected overpressure will be more than twice the value of the peak overpressure of the incident blast wave. The exact value of the peak reflected pressure (§§ 3.50, 3.71) will depend on the strength of the incident wave and the angle at which it strikes

the surface. The variation in overpressure with time, as observed at a point actually on the surface not too far from ground zero,[1] such as A in Fig. 3.17, is depicted in Fig. 3.18 for an ideal shock front. The point A may be considered as lying within the region of "regular" reflection, i.e., where the incident and reflected waves do not merge except on the surface.

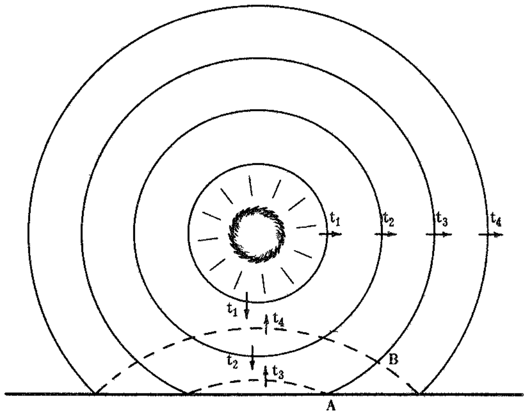


Figure 3.17. Reflection of blast wave at the earth's surface in an air burst; t_1 to t_4 represent successive times.

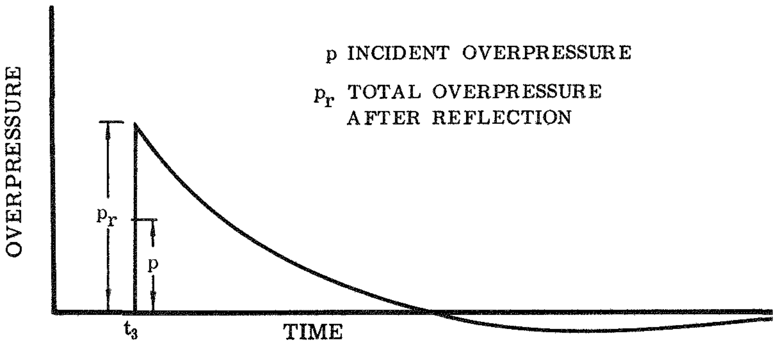


Figure 3.18. Variation of overpressure with time at a point on the surface in the region of regular reflection.

3.19 At any location somewhat above the surface in this region, two separate shocks will be felt, the first being due to the incident blast wave and the second to the reflected wave, which arrives a short time later (Fig. 3.19). This situation can be illustrated by considering the point B in Fig. 3.17, which is also in the regular

[1] For an explanation of the term "ground zero," see § 2.34.

reflection region. When the incident wave front reaches this point, at time t_3, the reflected wave is still some distance away. There will, consequently, be a short interval before the reflected wave reaches the point above the surface at time t_4. Between t_3 and t_4, the reflected wave has spread out to some extent, so that its peak overpressure will be less than the value obtained at surface level. In determining the effects of air blast on structures in the regular reflection region, it may be necessary to consider the magnitude and also the directions of motion of both the incident and reflected waves. After passage of the reflected wave, the transient wind near the surface becomes essentially horizontal.

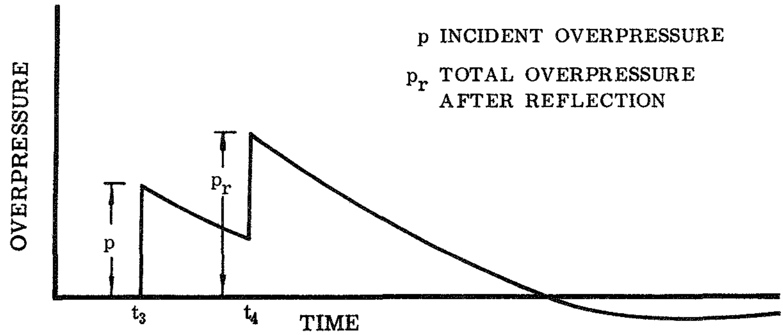


Figure 3.19. Variation of overpressure with time at a point above the surface in the region of regular reflection.

THE MACH EFFECT

3.20 The foregoing discussion concerning the delay between the arrival of the incident and reflected wave fronts at a point above the surface, such as B in Fig. 3.17, is based on the tacit assumption that the two waves travel with approximately equal velocities. This assumption is reasonably justified in the early stages, when the wave front is not far from ground zero. However, it will be evident that the reflected wave always travels through air that has been heated and compressed by the passage of the incident wave. As a result, the reflected wave front moves faster than the incident wave and, under certain conditions, eventually overtakes it so that the two wave fronts fuse to produce a single front. This process of wave interaction is called "Mach" or "irregular" reflection. The region in which the two waves have merged is therefore called the Mach (or irregular) region in contrast to the regular region where they have not merged.

3.21 The fusion of the incident and reflected waves is indicated schematically in Fig. 3.21, which shows a portion of the profile of the blast wave close to the surface. Fig. 3.21a represents the situation at a point fairly close to ground zero, such as A in Fig. 3.17. At a later stage, farther from ground zero, as in Fig. 3.21b, the steeper front of the reflected wave shows that it is traveling faster than, and is overtaking, the incident wave. At the stage represented by Fig. 3.21c, the reflected wave near the ground has overtaken and fused with the incident wave to form a single front called the "Mach stem." The point at which the incident wave, reflected wave, and Mach fronts meet is called the "triple point."[2]

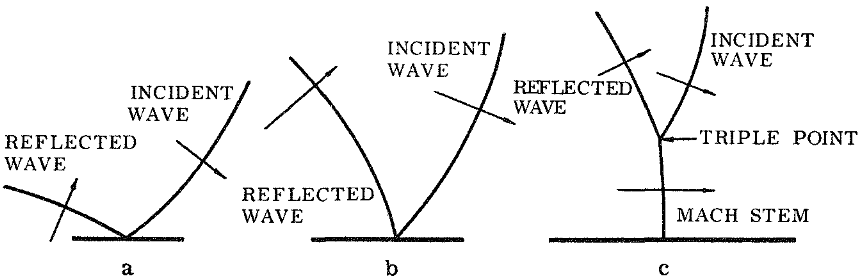


Figure 3.21. Fusion of incident and reflected waves and formation of Mach stem.

3.22 As the reflected wave continues to overtake the incident wave, the triple point rises and the height of the Mach stem increases (Fig. 3.22). Any object located either at or above the ground, within the Mach region and below the triple point path, will experience a single shock. The behavior of this fused or Mach wave is the same as that previously described for blast waves in general. The overpressure at a particular location will fall off with time and the positive (compression) phase will be followed by a negative (suction) phase, as in Fig. 3.06.

3.23 At points in the air above the triple point path, such as at an aircraft or at the top of a high building, two pressure increases will be felt. The first will be due to the incident blast wave and the second, a short time later, to the reflected wave. When a weapon is detonated at the surface, i.e., in a contact surface burst, only a single merged wave develops. Consequently, only one pressure increase will be observed either on or above the ground.

[2] At any instant the so-called "triple point" is not really a point, but a horizontal circle with its center on the vertical line through the burst point; it appears as a point on a drawing, such as Fig. 3.21c.

3.24 As far as the destructive action of the air blast is concerned, there are at least two important aspects of the reflection process to which attention should be drawn. First, only a single pressure increase is experienced in the Mach region below the triple point as compared to the separate incident and reflected waves in the region of regular reflection. Second, since the Mach stem is nearly vertical, the accompanying blast wave is traveling in a horizontal direction at the surface, and the transient winds are approximately parallel to the ground (Fig. 3.21). Thus, in the Mach region, the blast forces on aboveground structures and other objects are directed nearly horizontally, so that vertical surfaces are loaded more intensely than horizontal surfaces.

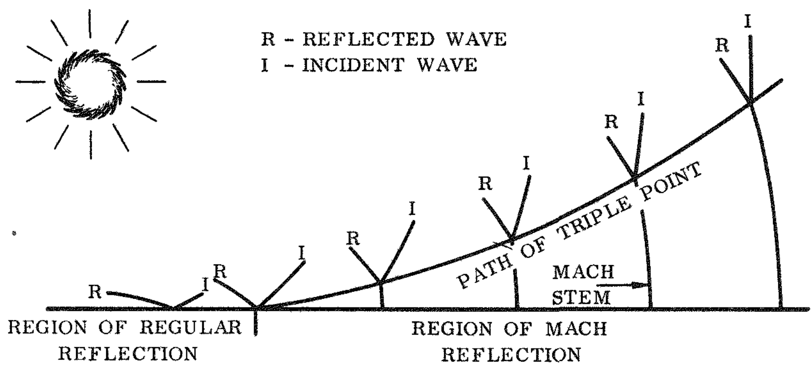


Figure 3.22. Outward motion of the blast wave near the surface in the Mach region.

3.25 The distance from ground zero at which Mach fusion commences and the Mach stem begins to form depends upon the yield of the detonation and the height of the burst above the ground. Provided the height of burst is not too great, the Mach stem forms at increasing distances from ground zero as the height of burst increases for a given yield, and also as the yield decreases at a specified height of burst. For moderate heights of burst Mach fusion occurs at a distance from ground zero approximately equal to the burst height. As the height of burst is increased, the distance from ground zero at which the Mach effect commences exceeds the burst height by larger and larger amounts.

Height of Burst and Blast Damage

3.26 The height of burst and energy yield (or power) of the nuclear explosion are important factors in determining the extent of damage at the surface. These two quantities generally define the variation of pressure with distance from ground zero and other associated blast wave characteristics, such as the distance from ground zero at which the Mach stem begins to form. As the height of burst for an explosion of given energy yield is decreased, or as the energy yield for a given height of burst increases, the consequences are as follows: (1) Mach reflection commences nearer to ground zero, and (2) the overpressure at the surface near ground zero becomes larger. An actual contact surface burst leads to the highest possible overpressures near ground zero. In addition, cratering and ground shock phenomena are observed, as will be described in Chapter VI.

3.27 Because of the relation between height of burst and energy of the explosion, the air blast phenomena to be expected on the ground from a weapon of large yield detonated at a height of several thousand feet will approach those of a near surface burst. On the other hand, explosions of weapons of smaller energy yields at these same or even lower levels will have the characteristics of air bursts. A typical example of the latter situation is found in the nuclear explosion which occurred over Nagasaki, Japan, in World War II when a weapon having a yield of approximately 20 kilotons of TNT equivalent was detonated at a height of about 1,850 ft. By means of certain rules, called "scaling laws," which are described in the technical section of this chapter (§ 3.55), it is found that to produce similar blast phenomena at ground distances proportional to the heights of burst, for a 1-kiloton weapon the height of burst would have to be roughly 680 feet and for a 1-megaton explosion about 6,800 feet. In these three cases, the Mach stem formation would occur at distances from ground zero that are not very different from the respective heights of burst.

3.28 It should be noted that there is no single optimum height of burst, with regard to blast effects, for any specified explosion yield because the chosen burst height will be determined by the nature of the target. As a rule, strong (or hard) targets will require the equivalent of a low air burst or a surface burst. For weaker targets, which are destroyed or damaged at relatively low overpressures or dynamic pressures, the height of burst may be raised to increase the damage areas, since the required pressures will extend to a larger range than for a low air or surface burst.

TECHNICAL ASPECTS OF BLAST WAVE PHENOMENA [4]

Properties of the Blast Wave

3.47 The characteristics of the blast wave have been discussed in a qualitative manner in the earlier parts of this chapter, and the remaining sections will be devoted to a consideration of some of the quantitative aspects of blast wave phenomena in air. The basic relationships among the properties of a blast wave, having a sharp front at which there is a sudden pressure discontinuity, i.e., a true (or ideal) shock front, are derived from the Rankine-Hugoniot conditions based on the conservation of mass, energy, and momentum at the shock front. These conditions, together with the equation of state for air, permit the derivation of the required relations involving the shock velocity, the particle (or wind) velocity, the overpressure, the dynamic pressure, and the density of the air behind the ideal shock front.

3.48 The blast wave properties in the region of regular reflection are somewhat complex and depend on the angle of incidence of the wave with the ground and the overpressure. For a contact surface burst, when there is but a single hemispherical (fused) wave, as stated in § 3.30, and in the Mach region below the triple point path for an air burst, the various blast wave characteristics at the shock front are uniquely related by the Rankine-Hugoniot equations. It is for these conditions, in which there is a single shock front, that the following results are applicable.

3.49 The shock velocity, U, is expressed by

$$U=c_0\left(1+\frac{\gamma+1}{2\gamma}\cdot\frac{p}{P_0}\right)^{1/2},$$

where c_0 is the ambient speed of sound (ahead of the shock front), p is the peak overpressure (behind the shock front), P_0 is the ambient pressure (ahead of the shock), and γ is the ratio of the specific heats of the medium, i.e., air. If γ is taken as 1.4, which is the value at moderate temperatures, the equation for the shock velocity becomes

$$U=c_0\left(1+\frac{6p}{7P_0}\right)^{1/2}$$

[4] The remaining sections of this chapter may be omitted without loss of continuity.

The particle velocity (or peak wind velocity behind the shock front), u, is given by

$$u = \frac{c_0 p}{\gamma P_0}\left(1+\frac{\gamma+1}{2\gamma}\cdot\frac{p}{P_0}\right)^{-1/2}$$

so that for air

$$u = \frac{5p}{7P_0}\cdot\frac{c_0}{(1+6p/7P_0)^{1/2}}.$$

The density, ρ, of the air behind the shock front is related to the ambient density, ρ_0, by

$$\frac{\rho}{\rho_0} = \frac{2\gamma P_0+(\gamma+1)p}{2\gamma P_0+(\gamma-1)p}$$

$$= \frac{7+6p/P_0}{7+p/P_0}.$$

The dynamic pressure, q, is defined by

$$q = \tfrac{1}{2}\rho u^2,$$

and the introduction of the appropriate Rankine-Hugoniot equations leads to the relation

$$q = \frac{p^2}{2\gamma P_0+(\gamma-1)p}$$

$$= \frac{5}{2}\cdot\frac{p^2}{7P_0+p} \tag{3.49.1}$$

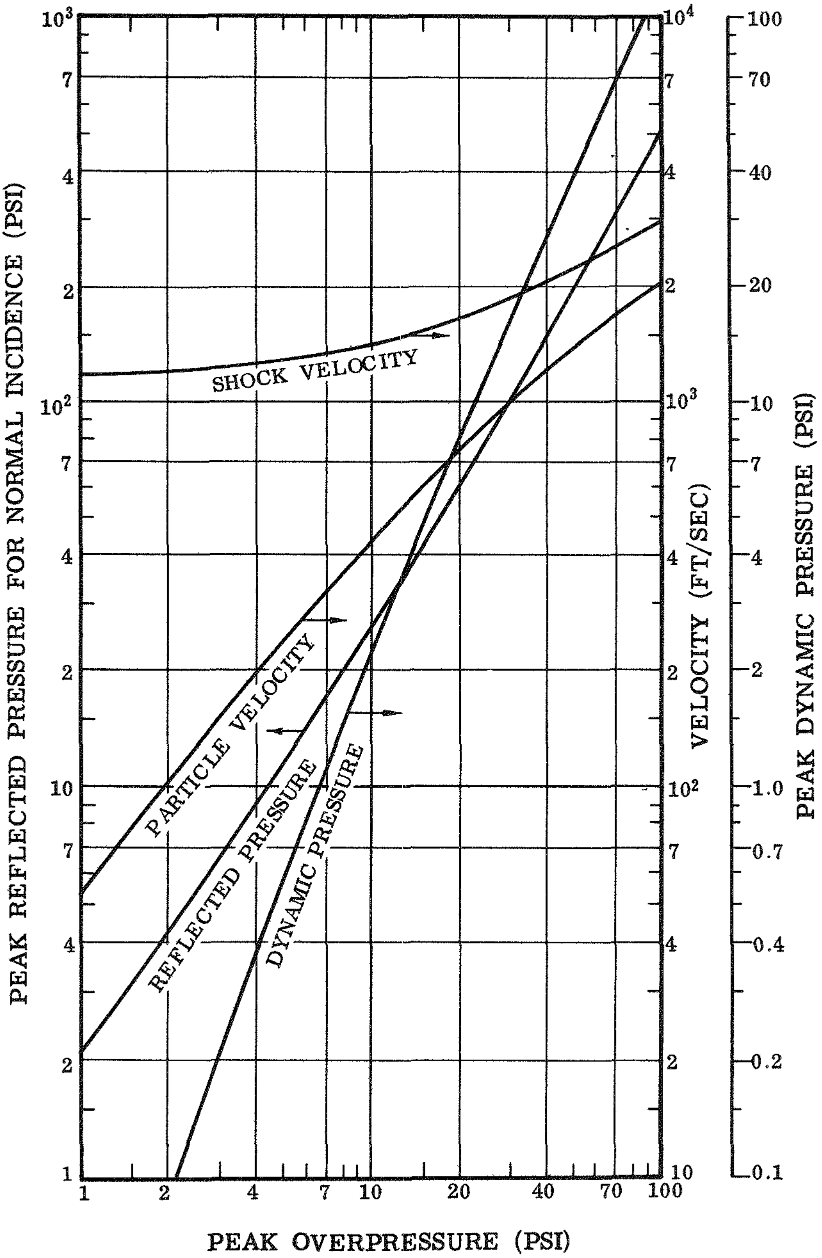
between the peak dynamic pressure in air and the peak overpressure and ambient pressure. The variations of shock velocity, particle (or peak wind) velocity, and peak dynamic pressure with the peak overpressure at sea level, as derived from the foregoing equations, are shown graphically in Fig. 3.49.

3.50 When the blast wave strikes a flat surface, such as that of a structure, at normal incidence, i.e., head on, the instantaneous (peak) value of the reflected overpressure, p_r, is given by

$$p_r = 2p+(\gamma+1)q, \tag{3.50.1}$$

and using equation (3.49.1) for air, this becomes

$$p_r = 2p\left(\frac{7P_0+4p}{7P_0+p}\right). \tag{3.50.2}$$



ure 3.49. Relation of ideal blast wave characteristics at the shock front to peak overpressure.

It can be seen from equation (3.50.2) that the value of p_r approaches $8p$ for very large values of the incident overpressure and dynamic pressure (strong shocks), and tends toward $2p$ for small overpressures and small dynamic pressures (weak shocks). It is evident from equation (3.50.1) that the increase in the reflected overpressure above the expected value of twice the incident value, i.e., $2p$, is due to the dynamic (or wind) pressure. The reflected overpressure arises from the change of momentum when the moving air changes direction as a result of striking the surface. A curve showing the variation of the instantaneous (peak) reflected pressure, with the peak incident overpressure, for normal incidence, is included in Fig. 3.49.

3.51 The equations in § 3.49 give the peak values of the various blast wave parameters at the shock front. As seen earlier, however, the overpressure and dynamic pressure both decrease with time, although at different rates. Provided the peak overpressure is low, e.g., about 10 pounds per square inch or less, the variation of the overpressure behind the shock front with time at a given point can be represented to a good approximation by the simple empirical equation

$$p(t)=p\left(1-\frac{t}{t_+}\right)e^{-t/t_+}, \tag{3.51.1}$$

where $p(t)$ is the overpressure at any time, t, after the arrival of the shock front, p is the peak overpressure, and t_+ is the duration of the positive phase. In the event of the interaction of the blast wave with a structure, this equation is used to determine the air blast loading as a function of time for low overpressures.

3.52 Strictly speaking, the rate of decay of the normalized overpressure behind the shock front is a function of the peak overpressure. This may be expressed mathematically by a series of exponential equations similar in form to equation (3.51.1). A set of such equations is represented graphically in Fig. 3.52, which shows the "normalized overpressure," i.e., the value relative to the peak overpressure, as a function of the "normalized time," i.e., the time relative to the duration of the positive phase, for various peak overpressure values. These have been developed by the numerical integration of the differential equations of gas motion for a spherical blast wave in air.

3.53 For low values of the peak dynamic pressure, the variation with time behind the shock front may be expressed, with fair accuracy, by an empirical expression similar to equation (3.51.1); thus,

$$q(t)=q\left(1-\frac{t}{t_+}\right)^2 e^{-2t/t_+},$$

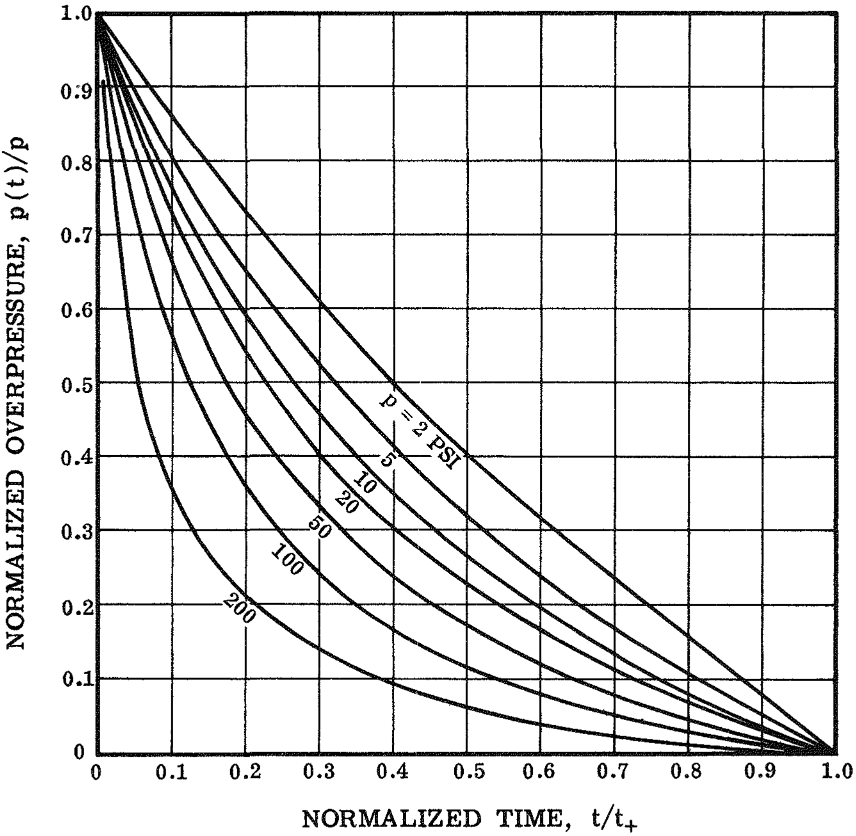


Figure 3.52. Rate of decay of pressure with time for various values of the peak overpressure.

where $q(t)$ is the value of the dynamic pressure at any time, t, after the arrival of the shock front, and q is the peak dynamic pressure. However, as is the case with the overpressure, the rate of decrease of the normalized dynamic pressure is dependent on the overpressure. This is shown by the curves in Fig. 3.53 which are for several indicated values of the peak overpressure. The time in this figure is normalized with respect to the duration of the dynamic pressure positive phase which is somewhat longer than that for the overpressure (§§3.16, 3.69).

3.54 Another important blast damage parameter is the "impulse," which takes into account the duration of the positive phase and the variation of the overpressure during that time. Impulse (per unit

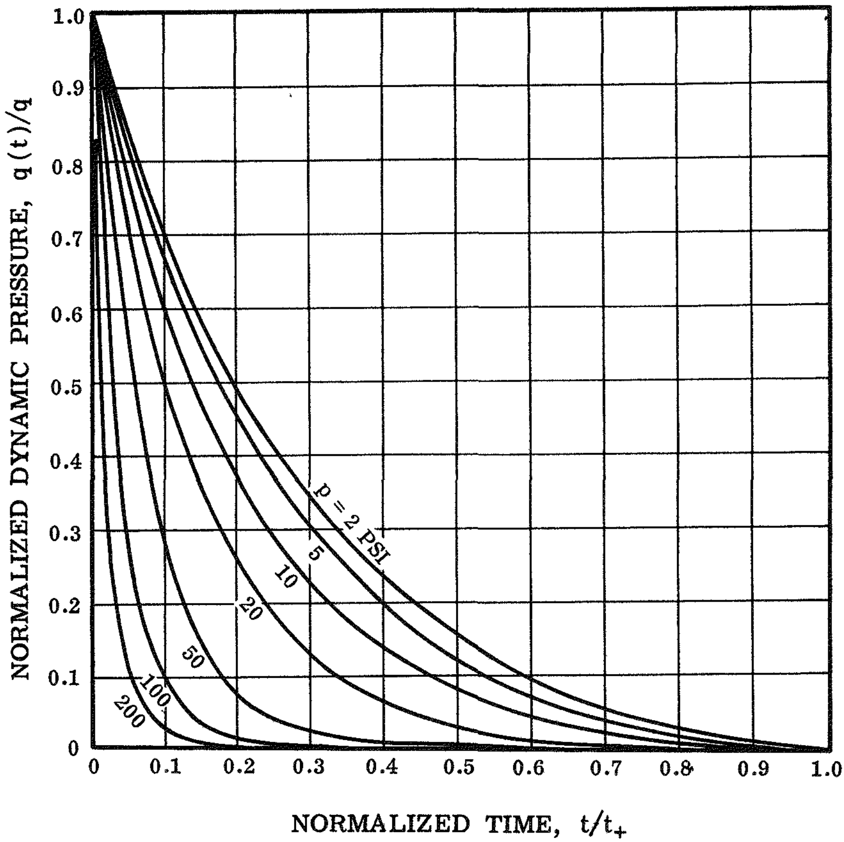


Figure 3.53. Rate of decay of dynamic pressure with time for various values of the peak overpressure.

area) may be defined as the total area under the overpressure-time curve, such as those shown in Fig. 3.52. The positive phase overpressure impulse (per unit area), I, may then be represented mathematically by

$$I=\int_0^{t_+} p(t)dt,$$

where $p(t)$ may be expressed analytically for low overpressures by means of equation (3.51.1). The positive phase dynamic impulse can be defined by a similar expression in which $q(t)$ replaces $p(t)$.

SCALING LAWS

3.55 In order to be able to calculate the characteristic properties of the blast wave from an explosion of any given energy if those for another energy are known, appropriate scaling laws are applied. With the aid of such laws it is possible to express the data for a large range of energies in a simple form. One way of doing this, which will be illustrated below, is to draw curves showing how the various properties of the blast wave at the surface change with increasing distance from the detonation in the case of a 1-kiloton nuclear explosion. Then, with the aid of the scaling laws, the values for an explosion of any specified energy can be readily determined for a particular height of burst.

3.56 Theoretically, a given pressure will occur at a distance from an explosion that is proportional to the cube root of the energy yield. Full scale tests have shown this relationship between distance and energy yield to hold for yields up to (and including) the megaton range. Thus, cube root scaling may be applied with confidence over a wide range of explosion energies. According to this law, if D_1 is the distance (or slant range) from a reference explosion of W_1 kilotons at which a certain overpressure or dynamic pressure is attained, then for any explosion of W kilotons energy these same pressures will occur at a distance D given by

$$\frac{D}{D_1}=\left(\frac{W}{W_1}\right)^{1/3}. \tag{3.56.1}$$

As stated above, the reference explosion is conveniently chosen as having an energy yield of 1 kiloton, so that $W_1=1$. It follows, therefore, from equation (3.56.1) that

$$D=D_1\times W^{1/3}, \tag{3.56.2}$$

where D_1 refers to the distance from a 1-kiloton explosion. Consequently, if the distance D is specified, then the value of the explosion energy, W, required to produce a certain effect, e.g., a given peak overpressure, can be calculated. Alternatively, if the energy, W, is specified, the appropriate distance, D, can be evaluated from equation (3.56.2).

3.57 When comparing air bursts having different energy yields, it is convenient to introduce a scaled height of burst, defined as

$$\text{Scaled height of burst}=\frac{\text{Actual height of burst}}{W^{1/3}}.$$

It can be readily seen, therefore, that for explosions of different energies having the same scaled height of burst, the cube root scaling law may be applied to distances from ground zero, as well as to distances from the explosion. Thus, if d_1 is the distance from ground zero at which a particular overpressure or dynamic pressure occurs for a 1-kiloton explosion, then for an explosion of W kilotons energy the same pressures will be observed at a distance d determined by the relationship

$$d=d_1\times W^{1/3}. \tag{3.57.1}$$

This expression can be used for calculations of the type referred to in the preceding paragraph, except that the distances involved are from ground zero instead of from the explosion (slant ranges).

3.58 Cube root scaling can also be applied to arrival time of the shock front, positive phase duration, and impulse, with the understanding that the distances concerned are themselves scaled according to the cube root law. The relationships may be expressed in the form

$$\frac{t}{t_1}=\frac{d}{d_1}=\left(\frac{W}{W_1}\right)^{1/3} \quad \text{and} \quad \frac{I}{I_1}=\frac{d}{d_1}=\left(\frac{W}{W_1}\right)^{1/3},$$

where t_1 represents arrival time or positive phase duration and I_1 is the impulse for a reference explosion of energy W_1, and t and I refer to any explosion of energy W; as before, d_1 and d are distances from ground zero. If W_1 is taken as 1 kiloton, then the various quantities are related as follows:

$$t=t_1\times W^{1/3} \text{ at a distance } d=d_1\times W^{1/3}$$

and

$$I=I_1\times W^{1/3} \text{ at a distance } d=d_1\times W^{1/3}.$$

Examples of the use of the equations developed above will be given later.

Altitude Corrections

3.59 The data presented (§ 3.49 *et seq*) for the characteristic properties of a blast wave are strictly applicable to a homogeneous atmosphere at sea level. For bursts up to about 5,000 feet altitude this condition holds, at least approximately, and the scaling equations given above may be used. If it is required to determine the air blast parameters at altitudes where the ambient atmospheric conditions are appreciably different from those at sea level, then the correction factor referred to in § 3.41 must be applied.

3.60 The general relationships which take into account the fact that the absolute temperature T and ambient pressure P are not the same as T_0 and P_0, respectively, in the reference (1-kiloton) explosion in a sea-level atmosphere, are as follows. For the overpressure,

$$p=p_1\frac{P}{P_0},$$

where p is the overpressure at altitude and p_1 is that at sea-level. The corrected value of distance for the new overpressure level is then given by

$$d=d_1W^{1/3}\left(\frac{P_0}{P}\right)^{1/3},$$

and for arrival time or positive phase duration at this new distance by

$$t=t_1W^{1/3}\left(\frac{P_0}{P}\right)^{1/3}\left(\frac{T_0}{T}\right)^{1/2}.$$

For impulse at altitude, the appropriate relationship is

$$I=I_1W^{1/3}\left(\frac{P}{P_0}\right)^{2/3}\left(\frac{T_0}{T}\right)^{1/2}.$$

It should be understood that the foregoing expressions are applicable when the altitude at the observation point (or target) does not differ by more than a few thousand feet from that at the point of burst. If the altitudes differ considerably, the situation is more complicated, as noted in § 3.42.

3.61 It is seen that when T is equal to T_0 and P to P_0, these expressions become identical with the corresponding ones in §§ 3.57 and 3.58, for strictly homogeneous conditions. As a general rule, the reference values for the blast wave properties, such as those to be given shortly, are for a standard sea-level atmosphere, where P_0 is 14.7 pounds per square inch and the temperature is 59° F or 15° C, so that T_0 is 519° Rankine or 288° Kelvin. As indicated previously, for bursts at elevations within 5,000 feet or so above sea level, the corrections will be small.

3.62 The scaling laws for altitude given above can be used provided the proportion of the explosion energy appearing as blast is approximately the same as at sea level. At heights of burst in excess of 100,000 feet (about 20 miles), however, the percentage of blast energy decreases (§2.119). The mechanism of shock formation apparently changes, too, at these altitudes, so that the scaling laws are no longer

applicable. In general, blast effects on the ground are determined by the energy yield of the explosion and the altitude of burst, both of which affect the amount of energy appearing in the blast wave and its subsequent propagation down through the nonhomogeneous atmosphere. For a 1-megaton weapon exploded 30 miles above the surface, the peak overpressures on the ground are expected to be less than 0.1 pound per square inch, compared with 0.4 pound per square inch at a distance of 30 miles from a burst at a height of 1 mile.

Standard Curves and Calculations of Blast Wave Properties

3.63 In order to estimate the damage which might be expected to occur at a particular range from a given explosion, it is necessary to define the characteristics of the blast wave as they vary with time and distance. Consequently, standard "height of burst" curves of the various air blast wave properties are given here to supplement the general discussion already presented. These curves show the variation of peak overpressure, peak dynamic pressure, arrival time, and positive phase duration with distance from ground zero for various heights of burst over a nearly-ideal surface. Similar curves may also be constructed for other blast wave parameters, but the ones presented here are generally considered to be the most useful. They apply to urban targets as well as to a wide variety of other approximately ideal situations.

3.64 From the curves given below the values of the blast wave properties at the surface can be calculated and the results used to determine the loading and response of a particular target. It should again be mentioned that the data represent the behavior of the blast wave under nearly-ideal conditions over a flat surface at (or near) sea level. Hence, the values of peak overpressure and dynamic pressure may be regarded as the basic information to be used in applying the procedures to be discussed in Chapter IV for the determination of blast damage to be expected under various conditions.

3.65 These standard curves show the blast wave properties for a 1-kiloton explosion. An example showing the use of the curves will be given on the page facing each figure. To simplify the calculations that will be made, Fig. 3.65 is provided; this gives the values of cube roots (n=0.33) required in the application of the scaling laws.[5]

3.66 The variations of peak overpressure and dynamic pressure with distance from ground zero for a 1-kiloton TNT equivalent con-

[5] Values of $W^{0.3}$, i.e., for n=0.3, are also included because they are used in Chapter VI.

722-454 O - 64 - 10

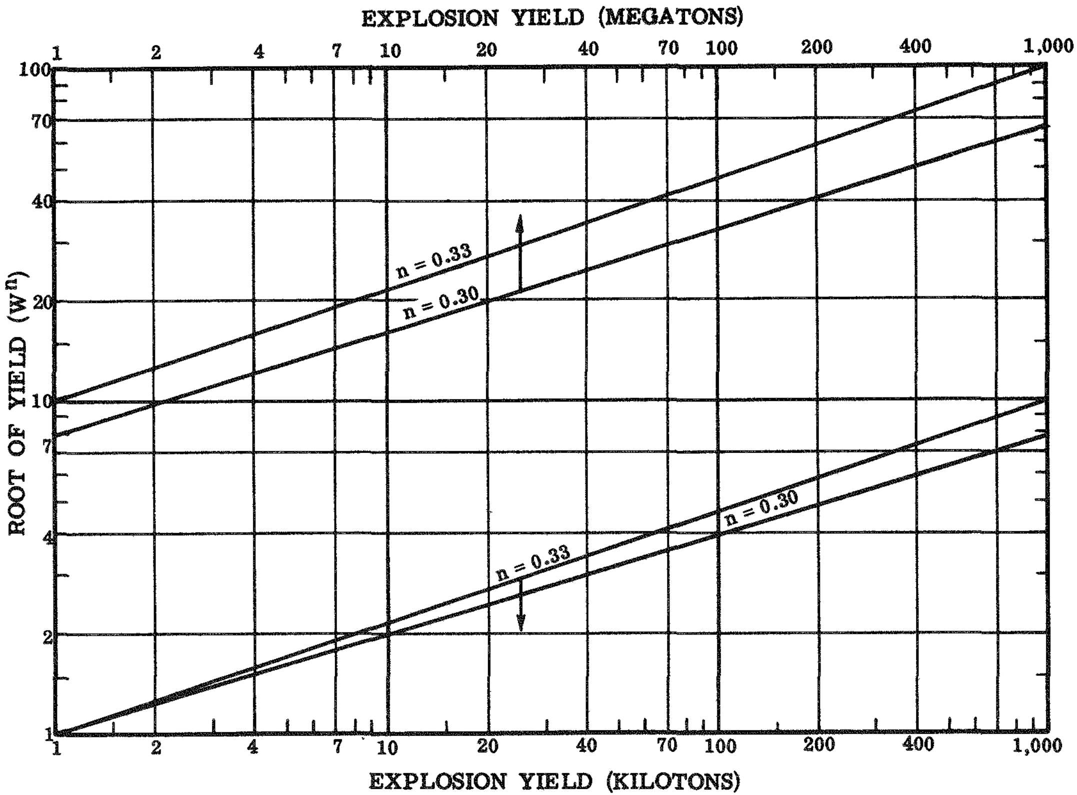


Figure 3.65. Values of $W^{0.33}$ ($W^{1/3}$) and $W^{0.3}$ for use in scaling calculations.

tact surface burst in a standard sea-level atmosphere are represented by the full curves in Fig. 3.66. The approximate range of the overpressure which may be expected under varying atmospheric conditions is indicated by the broken curves; the pressures will be higher than average if there is an inversion, i.e., air temperature increases with height above the ground, but they will be lower than average in an unstable atmosphere with no inversion, i.e., normal lapse rate.

3.67 The curves in Fig. 3.67a (high-pressure range) and Fig. 3.67b (low-pressure range) show the variation of peak overpressure, for a 1-kiloton air burst, with distance from ground zero as a function of the height of burst. The presence of a pronounced "knee" in the curves in the Mach region means that, for any given overpressure, there is an optimum burst height that maximizes the distance from ground zero at which this overpressure is experienced. The corresponding data for any other explosion energy yield may be obtained by use of the scaling laws. It will be noted that values of the ground distance for specific levels of peak overpressure in Fig. 3.66 may be derived from Figs. 3.67a and 3.67b by assuming the burst height to be zero, i.e., corresponding to a contact surface burst. Similar curves can be obtained for any height of burst by drawing a horizontal line across the figure at the desired burst height and reading off ground distances for specific values of the blast wave parameter.

3.68 The family of curves in Fig. 3.68 indicate the variation of the horizontal component of the peak dynamic pressure along the surface with distance from ground zero and height of burst for a 1-kiloton air burst in a standard sea-level atmosphere for nearly-ideal surface conditions. By assuming a height of burst of zero, the peak dynamic pressures in Fig. 3.66 for a surface burst are obtained.

3.69. The dependence of the positive phase duration of the overpressure and of the dynamic pressure on the distance from ground zero and on the height of burst is shown by the curves in Fig. 3.69; the values for the dynamic pressure duration are in parentheses. As in the other cases, the results apply to a 1-kiloton explosion in a standard sea-level atmosphere for a nearly-ideal surface. It will be noted, as mentioned earlier, that for a given detonation and location, the duration of the positive phase of the dynamic pressure is longer than that of the overpressure.

3.70 The curves in Figs. 3.70 a and b give the time of arrival of the shock front on the ground at various distances from ground zero as a function of the height of burst for a 1-kiloton explosion under the usual conditions of a sea-level atmosphere and a nearly-ideal surface.

3.71 The peak overpressures in Figs. 3.66, 3.67 a and b are those that would be observed at or near the surface of the ground after reflection has taken place. These peak values are considered to be the side-on overpressures (§ 4.07, footnote) to be used in determining target loading and response. However, further reflection is possible at the front face of a structure when it is struck by the blast wave. The magnitude of the reflected pressure $p_{r(\alpha)}$ depends on the side-on pressure p and the angle, α, between blast wave front and the struck surface (Fig. 3.71a). The values of the ratio $p_{r(\alpha)}/p$ as a function of angle of incidence for various indicated side-on pressures are given in Fig. 3.71b. It is seen that for normal incidence, that is when $\alpha=0°$, the ratio $p_{r(\alpha)}/p$ is approximately 2 at low overpressures and increases with the overpressure (§ 3.50). The curves in Fig. 3.71b are particularly applicable in the Mach region where an essentially vertical shock front moving radially strikes a reflecting surface such as the front wall of a structure (see Fig. 4.08).

The Precursor

3.72 The foregoing results have referred to blast wave conditions which are ideal or nearly ideal, so that the Rankine-Hugoniot equations are applicable (§ 3.47). In certain circumstances, however, the physical character of the surface may be such as to produce a non-ideal situation. As a result of intense thermal radiation from the nuclear explosion impinging on a heat-absorbing surface, such as desert, coral, or asphalt, a hot layer of air, referred to as a "thermal layer," is produced. The thermal layer, which often includes smoke, dust, and other particulate matter, forms before the arrival of the blast wave from an air burst, and interaction of the wave with the heated layer may affect the reflection process to a considerable extent. For appropriate combinations of explosion energy yield, low burst height, and heat-absorbing surfaces, an auxiliary blast wave, called a "precursor," will form and move ahead of the main incident wave for a limited distance. Severe modifications of the usual blast wave characteristics may occur within the precursor region. In particular, the pressure at the wave front increases more gradually but to a lower peak value than in a true shock wave, and the decay with distance is abnormal. Furthermore, the normal Rankine-Hugoniot relations at the shock front no longer apply. For these reasons, the precursor region is said to be non-ideal.

3.73 It should be noted that precursor formation is not to be expected over non-dusty and heat-reflecting surfaces, such as concrete, snow, ice, or water. Furthermore, thermal effects on the blast wave appear to be small for surface bursts and for high air bursts, regardless of yield and the type of surface. Consequently, it is believed that in many situations, especially in urban areas, nearly-ideal blast wave conditions would prevail.

(Text continued on page 148.)

The curves in Fig. 3.66 show the variation of peak overpressure and peak dynamic pressure with distance for a 1 KT surface burst in a standard sea-level atmosphere.

Scaling. For yields other than 1 KT, the range to which a given peak overpressure or dynamic pressure extends scales as the cube root of the yield, i.e.,

$$d=d_1\times W^{1/3},$$

where, for a given peak overpressure or dynamic pressure, d_1 is the distance from the explosion for 1 KT, and d is the distance from the explosion for W KT.

Example

Given: A 1 MT surface burst.

Find: The distance to which 2 psi extends.

Solution: From Fig. 3.65 the cube root of 1000 is 10. From Fig. 3.66, a peak overpressure of 2 psi occurs at a distance of 2,500 feet from a 1 KT surface burst. Therefore, for a 1 MT surface burst,

$$d=d_1\times W^{1/3}=2{,}500\times 10=25{,}000 \text{ feet}=4.7 \text{ miles.} \quad \textit{Answer.}$$

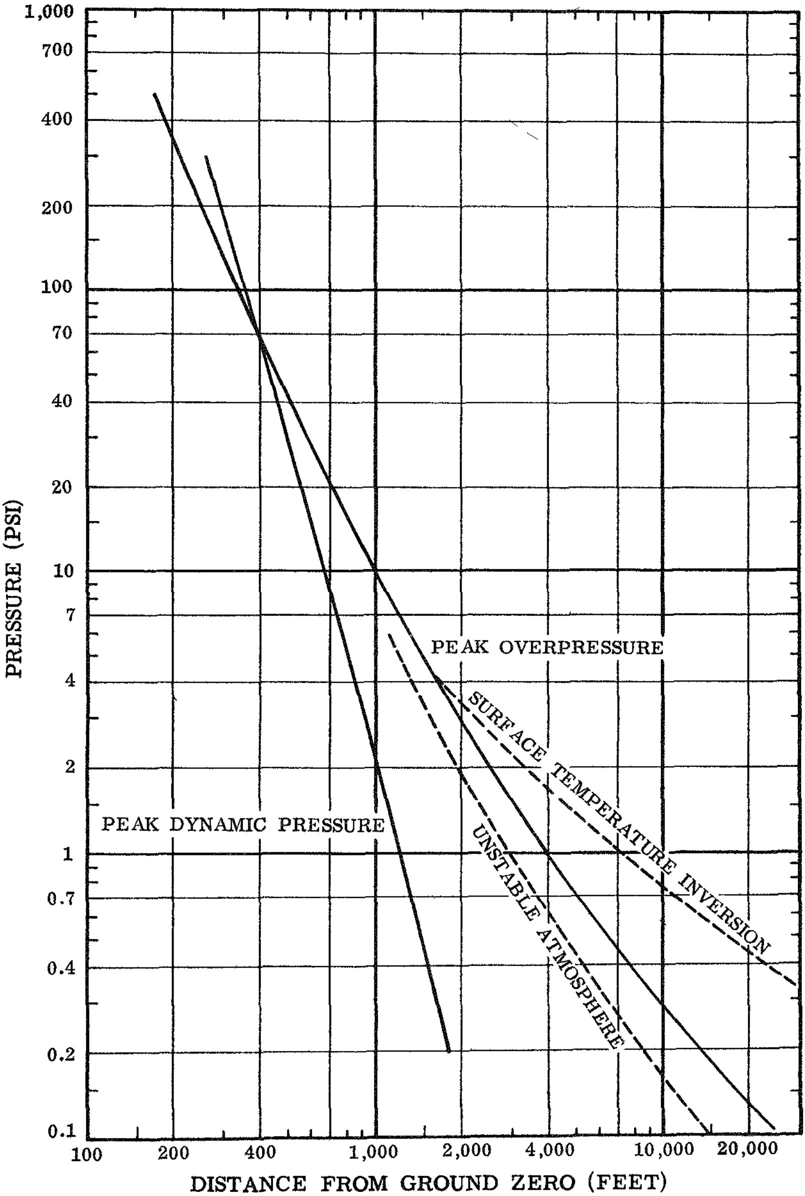


Figure 3.66. Peak overpressure and peak dynamic pressure for 1-kiloton surface burst.

The curves in Fig. 3.67a show peak overpressures on the ground in the high-pressure range as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The dashed line separates the regular reflection region from the Mach region and indicates where the triple point is formed (§ 3.20 *et seq.*). The data are considered appropriate to nearly-ideal target conditions. Surface influences are discussed in §§ 3.43, 3.44, and 3.72.

Scaling. The height of burst and the distance from ground zero to which a given peak overpressure extends scale as the cube root of the yield, i.e.,

$$\frac{d}{d_1}=\frac{h}{h_1}=W^{1/3},$$

where, for a given peak overpressure, d_1 and h_1 are distance from ground zero and height of burst for 1 KT, and d and h are the corresponding distance and height of burst for W KT.

Example

Given: An 80 KT detonation at 2,580 feet.

Find: The distance to which 50 psi extends.

Solution: The corresponding height of burst for 1 KT is

$$h_1=\frac{h}{W^{1/3}}=\frac{2,580}{(80)^{1/3}}=600 \text{ feet.}$$

From Fig. 3.67a, an overpressure of 50 psi extends to 215 feet for a 600-foot burst height for a 1 KT weapon. The corresponding distance for 80 KT is

$$d=d_1W^{1/3}=215\times(80)^{1/3}=925 \text{ feet.} \quad \textit{Answer}$$

The procedure to be used for calculating the peak overpressure at a specified distance is given on the page facing Fig. 3.68.

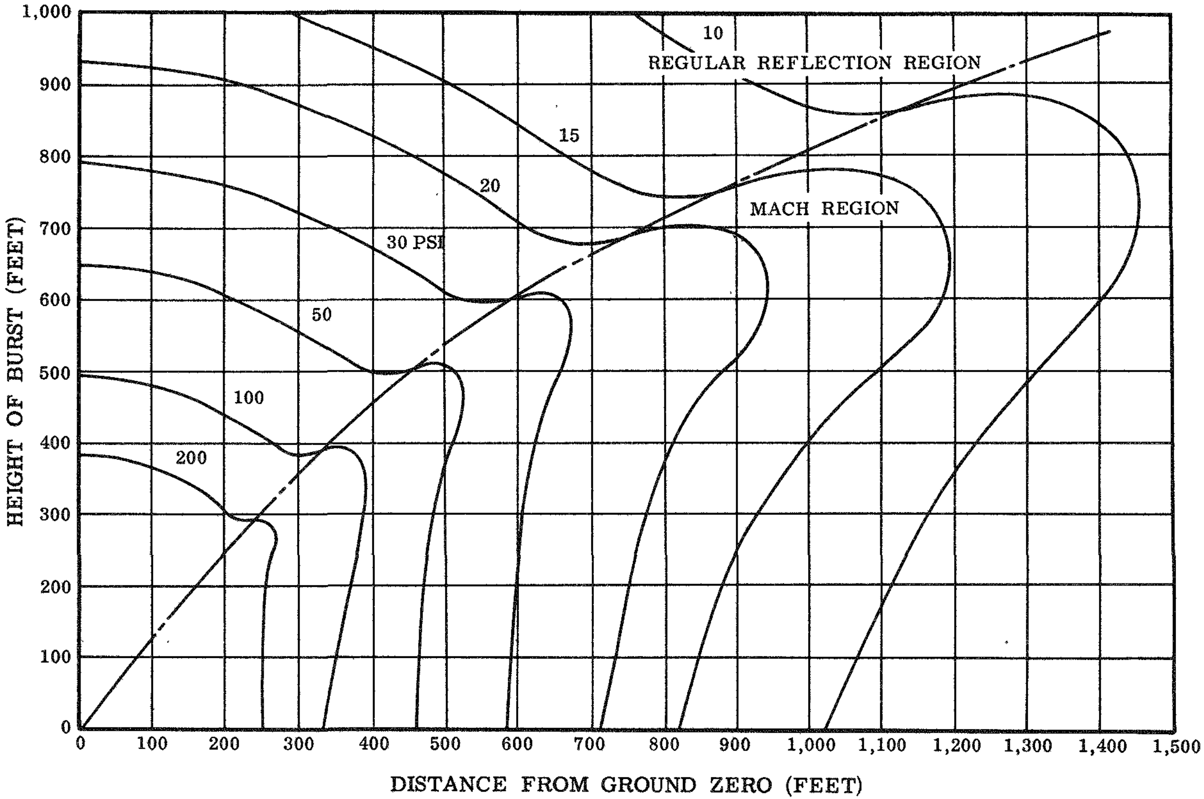


Figure 3.67a. Peak overpressures on the ground for a 1-kiloton burst (high-pressure range).

The curves in Fig. 3.67b show peak overpressures on the ground in the low-pressure range as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The broken line separates the regular reflection region from the Mach region and indicates where the triple point is formed (§ 3.20 *et seq.*). The data are considered appropriate for nearly-ideal target conditions. Surface influences are discussed in §§ 3.43, 3.44, and 3.72.

Scaling. The height of burst and the distance from ground zero to which a given peak overpressure extends scale as the cube root of the yield, i.e.,

$$\frac{d}{d_1}=\frac{h}{h_1}=W^{1/3},$$

where, for a given peak overpressure, d_1 and h_1 are the distance from ground zero and height of burst for 1 KT, and d and h are the corresponding distance and height of burst for W KT.

Example

Given: An 80 KT detonation at 2,580 feet.

Find: The distance to which 4 psi extends.

Solution: The corresponding height of burst for 1 KT is

$$h_1=\frac{h}{W^{1/3}}=\frac{2{,}580}{(80)^{1/3}}=600 \text{ feet.}$$

From Fig. 3.67b, 4 psi extends to 2,300 feet for a 600-foot burst height for a 1 KT weapon. The corresponding distance for 80 KT is

$$d=d_1W^{1/3}=2{,}300\times(80)^{1/3}=9{,}900 \text{ feet.} \quad \textit{Answer.}$$

The procedure to be used for calculating the peak overpressure at a specified distance is given on the page facing Fig. 3.68.

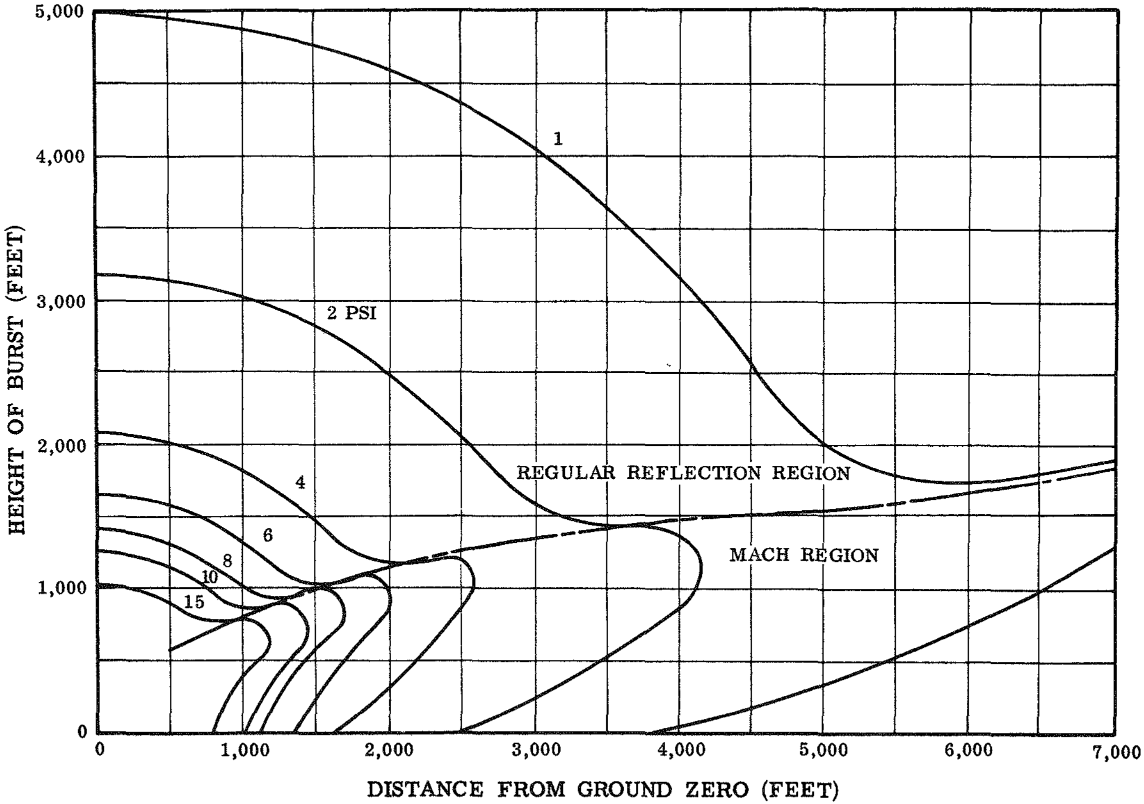


Figure 3.67b. Peak overpressures on the ground for 1-kiloton burst (low-pressure range).

The curves in Fig. 3.68 show the horizontal component of peak dynamic pressure on the ground as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The data are considered appropriate for nearly-ideal target conditions. Surface influences are discussed in §§ 3.43, 3.44, and 3.72.

Scaling. The height of burst and range to which a given peak dynamic pressure value extends scale as the cube root of the yield, i.e.,

$$\frac{d}{d_1}=\frac{h}{h_1}=W^{1/3},$$

where, for a given peak dynamic pressure, h_1 and d_1 are the height of burst and distance from ground zero for 1 KT, and h and d are the corresponding height of burst and distance for W KT.

Example

Given: A 160 KT burst at a height of 3,000 feet.

Find: The horizontal component of peak dynamic pressure on the ground at a range of 6,000 feet.

Solution: The corresponding height of burst for 1 KT is

$$h_1=\frac{h}{W^{1/3}}=\frac{3,000}{(160)^{1/3}}=550 \text{ feet.}$$

The corresponding range for 1 KT is

$$d_1=\frac{d}{W^{1/3}}=\frac{6,000}{(160)^{1/3}}=1,110 \text{ feet.}$$

From Fig. 3.68, at a range of 1,110 feet and a burst height of 550 feet, the horizontal component of the peak dynamic pressure is approximately 3 psi. *Answer.*

The procedure to be used for calculating the distance to which a given peak dynamic pressure extends is given on the pages facing Figs. 3.67 a and b.

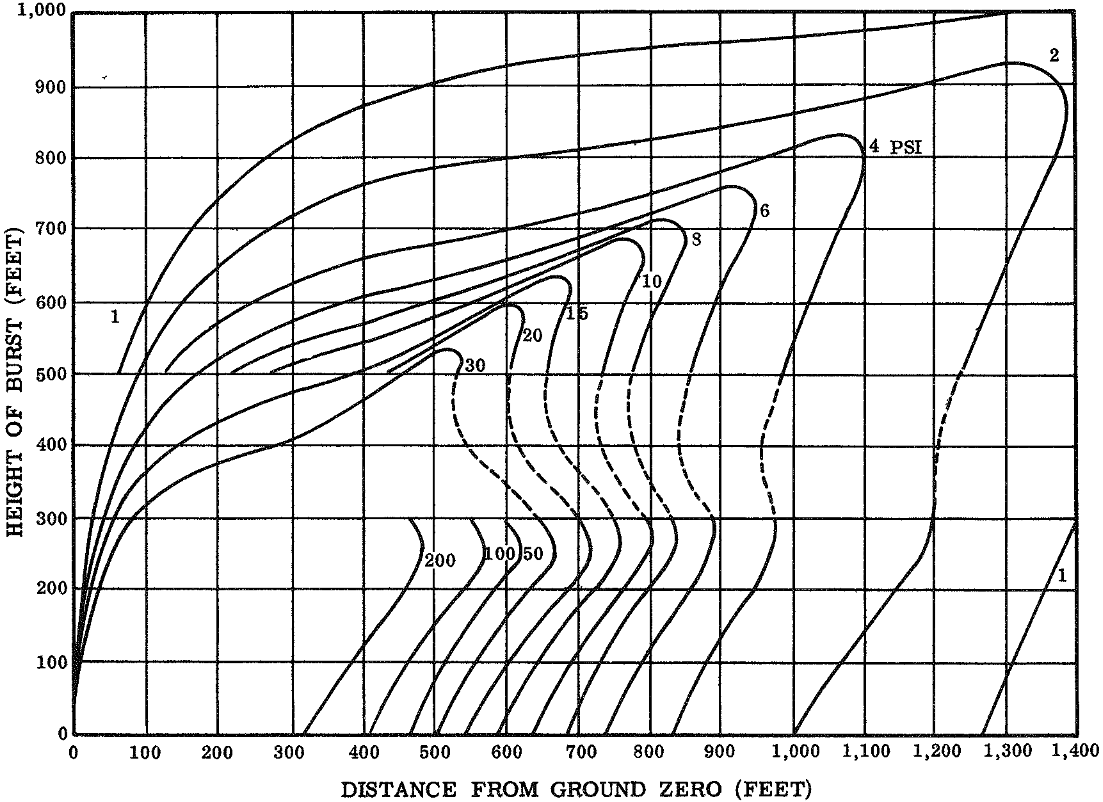


Figure 3.68. Horizontal component of peak dynamic pressure for 1-kiloton burst.

The curves in Fig. 3.69 show the duration on the ground of the positive phase of the overpressure and of the dynamic pressure (in parentheses) as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The curves are considered appropriate for nearly-ideal surface conditions.

Scaling. The required relationships are

$$\frac{d}{d_1}=\frac{h}{h_1}=\frac{t}{t_1}=W^{1/3},$$

where d_1, h_1, and t_1 are the distance from ground zero, the height of burst, and duration, respectively, for 1 KT; and d, h, and t are the corresponding distance, height of burst, and duration for W KT.

Example

Given: A 160 KT explosion at a height of 3,000 feet.

Find: The positive phase duration on the ground of (*a*) the overpressure, (*b*) the dynamic pressure at 4,000 feet.

Solution: The corresponding height of burst for 1 KT is

$$h_1=\frac{h}{W^{1/3}}=\frac{3{,}000}{(160)^{1/3}}=550 \text{ feet},$$

and the corresponding distance from ground zero is

$$d_1=\frac{d}{W^{1/3}}=\frac{4{,}000}{(160)^{1/3}}=740 \text{ feet}.$$

(*a*) From Fig. 3.69, the positive phase duration of the overpressure for 1 KT at 740 feet from ground zero and a burst height of 550 feet is 0.18 second. The corresponding duration of the overpressure positive phase for 160 KT is, therefore,

$$t=t_1W^{1/3}=0.18\times(160)^{1/3}=1.0 \text{ second.} \quad \textit{Answer}$$

(*b*) From Fig. 3.69, the positive phase duration of the dynamic pressure for 1 KT at 740 feet from ground zero and a burst height of 550 feet is 0.34 second. The corresponding duration of the dynamic pressure positive phase for 160 KT is, therefore,

$$t=t_1W^{1/3}=0.34\times(160)^{1/3}=1.8 \text{ second.} \quad \textit{Answer}$$

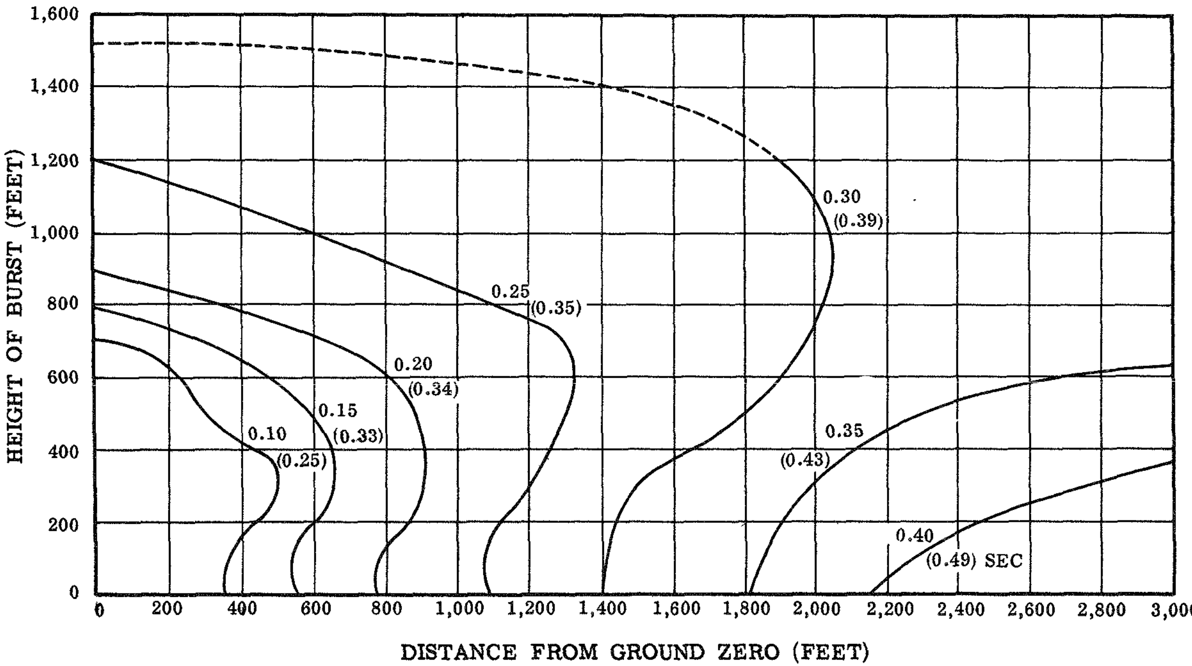


Figure 3.69. Positive phase duration on the ground of overpressure and dynamic pressure (in parentheses) for 1-kiloton burst.

The curves in Figs. 3.70 a and b give the time of arrival of the blast wave on the ground as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The curves are considered appropriate for nearly-ideal surface conditions.

Scaling. The required relationships are

$$\frac{d}{d_1}=\frac{h}{h_1}=\frac{t}{t_1}=W^{1/3},$$

where d_1, h_1, and t_1 are the distance from ground zero, height of burst, and time of arrival, respectively, for 1 KT; and d, h, and t are the corresponding distance, height of burst, and time for W KT.

Example

Given: A 1 MT explosion at a height of 5,000 feet.

Find: The time of arrival of the blast wave at a distance of 10 miles from ground zero.

Solution: The corresponding burst height for 1 KT is

$$h_1=\frac{h}{W^{1/3}}=\frac{5{,}000}{(1{,}000)^{1/3}}=500 \text{ feet.}$$

The corresponding distance from ground zero for 1 KT is

$$d_1=\frac{d}{W^{1/3}}=\frac{5{,}280\times 10}{(1{,}000)^{1/3}}=5{,}280 \text{ feet.}$$

From Fig. 3.70b, at a height of burst of 500 feet and a distance of 5,280 feet from ground zero, the arrival time is 4.0 seconds for 1 KT. The corresponding arrival time for 1 MT is

$$t=t_1W^{1/3}=4.0\times(1{,}000)^{1/3}=40 \text{ seconds.} \quad \textit{Answer}$$

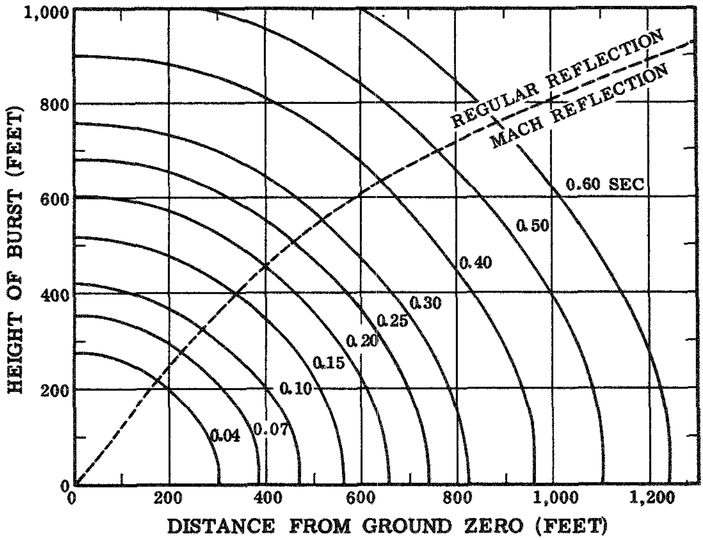


Figure 3.70a. Arrival times on the ground of blast wave for 1-kiloton burst (early times).

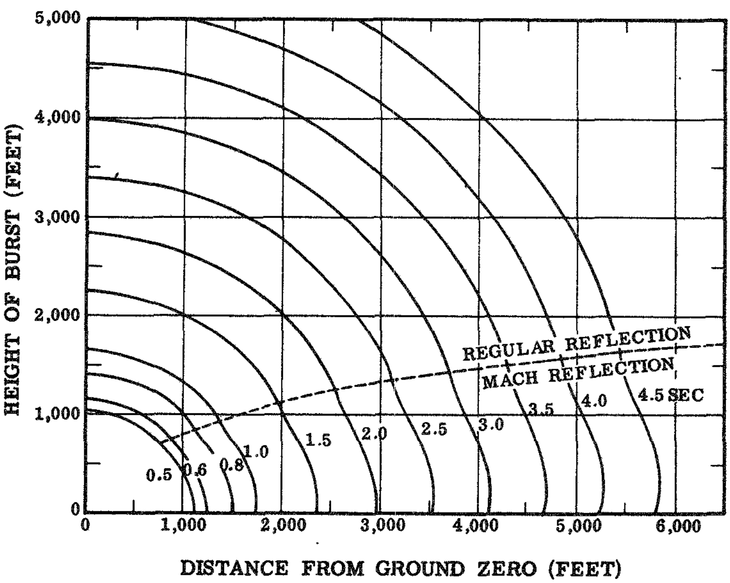


Figure 3.70b. Arrival times on the ground of blast wave for 1-kiloton burst (late times).

The reflected overpressure ratio $p_{r(\alpha)}/p$ is plotted in Fig. 3.71b as a function of the angle of incidence of the blast wave front for various values of the peak (side-on) overpressure. The curves apply to a wave front striking a reflecting surface, such as a wall of a structure.

$p_{r(\alpha)}$ = reflected blast wave overpressure for any given angle of incidence (psi).
p = initial peak incident overpressure (psi)
α = angle between the blast wave front and the reflecting surface (degrees)

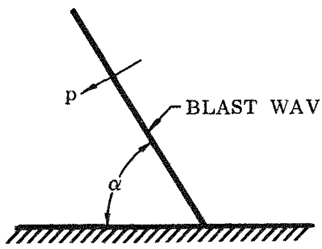


Figure 3.71a. Angle of incidence (α) of blast wave with reflecting surface.

Example

Given: A shock wave of 30 psi initial peak overpressure striking a surface at an angle of 35°.

Find: The reflected shock wave overpressure.

Solution: From Fig. 3.71b the reflected overpressure ratio, $p_{r(\alpha)}/p$, for 30 psi and an angle of incidence of 35° is 3.2; hence, $p_{r(35°)} = 3.2p = 3.2 \times 30 = 96$ psi. *Answer*

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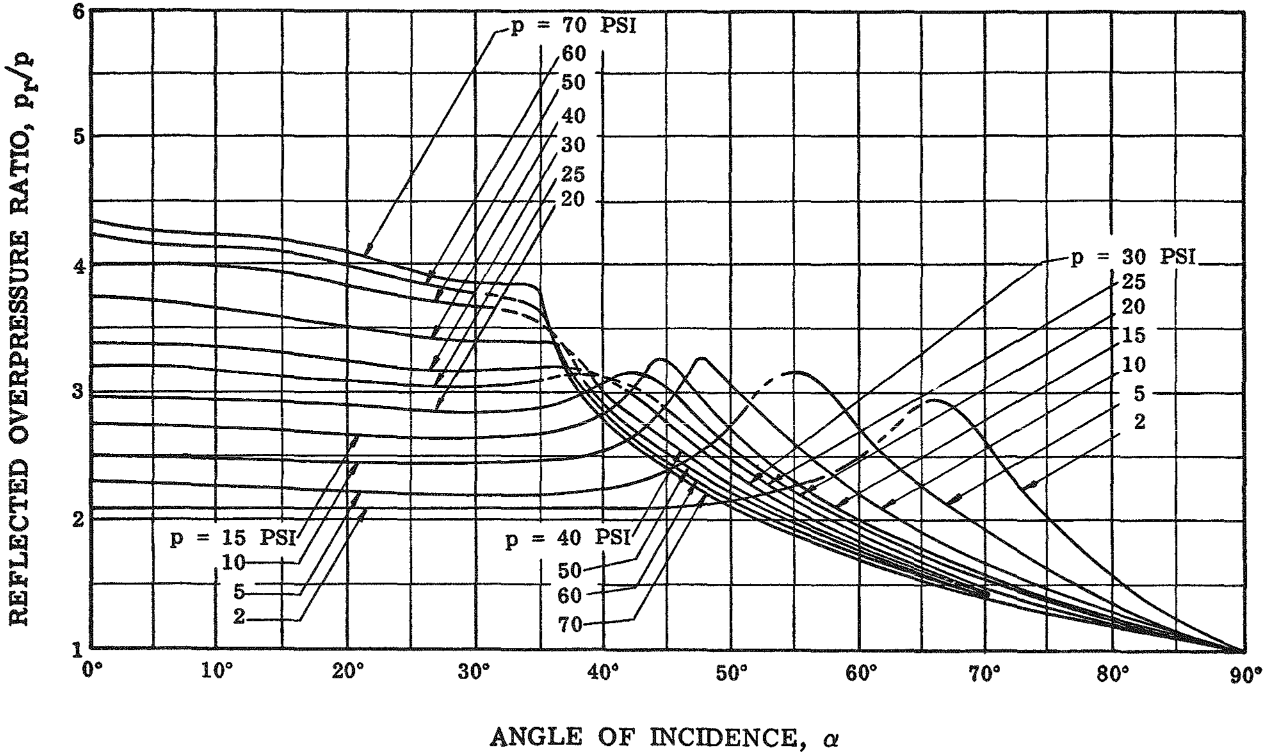

Figure 3.71b. Reflected overpressure ratio as function of angle of incidence for various side-on overpressures.

(Text continued from page 134.)

3.74 For this reason, the height of burst curves for various air blast parameters presented earlier apply to nearly-ideal surface conditions. These curves are considered to be the most representative for general use. However, it should be noted that empirical data obtained in the precursor region for low air bursts at the Nevada Test Site may reflect the non-ideal behavior of the blast wave with regard to both phenomena and damage. Under such circumstances the peak values of overpressure and dynamic pressure do not obey equation (3.49.1). In fact, the overpressure wave form may be irregular and show a slow rise to a peak value somewhat less than that expected for nearly-ideal conditions. Consequently, the peak value of reflected pressure on the front face of an object struck by the blast wave may not exceed the peak value of the incident pressure by more than a factor of two instead of the much higher theoretical factor for an ideal shock front as given by equation (3.50.2). Similarly, the dynamic pressure wave form may also be irregular, but the peak value may be several times that computed from the measured peak overpressure by the Rankine-Hugoniot relations for the reasons given in §3.44. Damage to and displacement of targets which are affected by the dynamic pressure may thus be considerably greater in the non-ideal precursor region for a given value of peak overpressure than under nearly-ideal conditions.

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*These documents may be obtained for a small charge from the Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C.

For most soils, however, this lateral blast pressure is likely to be somewhat higher and may approach 100 percent of the roof blast pressure in porous saturated soil. The pressures on the bottom of a buried structure, in which the bottom slab is a structural unit integral with the walls, may range from 75 to 100 percent of the pressure exerted on the roof.

4.44 Underground structures, buried at such a depth that the ratio of the burial depth to the span approaches (or exceeds) a value of 3.0, will obtain some benefit from the "arching effect" of the soil surrounding the structure. Limited experience at the Nevada Test Site has indicated that the arching action of the soil effectively reduces the loading on flexible structures, although the exact extent is at present uncertain.

4.45 The damage that might be suffered by a shallow buried structure will depend on a number of variables, including the structural characteristics, the nature of the soil, the depth of burial, and the downward pressure, i.e., the peak overpressure and direction of the blast wave. In Table 4.45 are given the limiting values of the peak overpressure required to cause various degrees of damage to two types of shallow buried structures. The range of pressures is intended to allow for differences in structural design, soil conditions, shape of earth mound, and orientation with respect to the blast wave.

4.46 An illustration of severe damage to a 10-gage corrugated steel-arch, earth-covered, surface structure is shown in Fig. 4.46. It

TABLE 4.45

DAMAGE CRITERIA FOR SHALLOW BURIED STRUCTURES

Type of structure	Damage type	Peak overpressure	Nature of damage
		psi	
Light, corrugated steel arch, surface structure (10-gage corrugated steel with a span of 20–25 ft), central angle of 180° with 5 ft of earth cover at the crown.*	Severe	45–60	Collapse.
	Moderate	40–50	Large deformations of end walls and arch, also major entrance door damage.
	Light	30–40	Damage to ventilation and entrance door.
Buried concrete arch with a 16 ft span and central angle of 180°; 8 in. thick with 4 ft of earth cover at the crown.	Severe	220–280	Collapse.
	Moderate	160–220	Large deformations with considerable cracking and spalling.
	Light	120–160	Cracking of panels, possible entrance door damge.

* In the case of arched structures reinforced with ribs, the collapse pressure is higher depending on the number of ribs.

Figure 4 46 Severe damage to earth-covered surface corrugated steel structure

will be noted that about half of the arch has collapsed This failure was attributed primarily to the dynamic pressure acting on the forward slope of the earth mound.

Damage to Land Transportation Equipment

4 47 The general types of land transportation equipment considered here include civilian motor-driven vehicles and earth-moving

equipment (bulldozers, graders, scrapers), and railroad rolling stock (locomotives and box, tank, and gondola cars). These items are primarily drag sensitive, i.e., they respond chiefly to the dynamic pressure, rather than to the air blast overpressure. The descriptions of the various degrees of damage are given in Table 4.47. The corresponding ranges as a function of explosion yield are represented graphically in Fig. 4.58b.

TABLE 4.47

DAMAGE CRITERIA FOR LAND TRANSPORTATION EQUIPMENT

Description of equipment	Damage	Nature of damage
Motor equipment (cars and trucks).	Severe	Gross distortion of frame, large displacements, outside appurtenances (door and hoods) torn off, need rebuilding before use.
	Moderate	Turned over and displaced, badly dented, frames sprung, need major repairs.
	Light	Glass broken, dents in body, possibly turned over, immediately usable.
Railroad rolling stock (box, flat, tank, and gondola cars).	Severe	Car blown from tracks and badly smashed, extensive distortion, some parts usable.
	Moderate	Doors demolished, body damaged, frame distorted, could possibly roll to repair shop.
	Light	Some door and body damage, car can continue in use.
Railroad locomotives (Diesel or steam).	Severe	Overturned, parts blown off, sprung and twisted, major overhaul required.
	Moderate	Probably overturned, can be towed to repair shop after being righted, need major repairs.
	Light	Glass breakage and minor damage to parts, immediately usable.
Construction equipment (bulldozers and graders).	Severe	Extensive distortion of frame amd crushing of sheet metal, extensive damage to tracks and wheels.
	Moderate	Some frame distortion, overturning, track and wheel damage.
	Light	Slight damage to cabs and housing, glass breakage.

DAMAGE TO PARKED TRANSPORT AIRCRAFT

4.48 Aircraft are relatively vulnerable to air blast effects associated with nuclear detonations. The forces developed by overpressures of 1 to 2 pounds per square inch are sufficient to dish in panels and buckle stiffeners and stringers. At higher overpressures, the drag forces due to wind (dynamic) pressure tend to rotate, translate, overturn, or lift a parked aircraft, so that damage may then result from collision with other aircraft, structures, or the ground. Aircraft are also very susceptible to damage from flying debris carried by the blast wave.

4.49 Several factors influence the degree of damage that may be expected for an aircraft of a given type at a specified range from a nuclear detonation. Aircraft that are parked with the nose pointed toward the burst will suffer less damage than those with the tail or either side directed toward the oncoming blast wave. Shielding of one aircraft by another or by structures or terrain features may reduce damage, especially that caused by flying debris. Standard tiedown of aircraft, as used when high winds are expected, will also minimize the extent of damage at ranges where destruction might otherwise occur.

4.50. The various damage categories for parked transport airplanes, light liaison airplanes, and helicopters are outlined in Table 4.50 together with the approximate overpressures at which the damage may be expected to occur. The estimated ranges for the different types of damage can be obtained by using the overpressure values in conjuction with the height of burst curves presented in Chapter III. The aircraft are considered to be parked in the open at random orientation with respect to the point of burst. It should be mentioned that the data are based on tests in which aircraft were exposed to detonations with yields in the kiloton range. For megaton yields, the longer duration of the positive phase of the blast wave may result in some increase in damage over that estimated from small-yield explosions at the same overpressure level. This increase is likely to be significant at pressures producing severe damage, but will probably be less important for moderate and light damage conditions. Since quantitative data are not available concerning the effect of detonations of high yield on aircraft, no allowance for it has been made in Table 4.50.

TABLE 4.50

DAMAGE CRITERIA FOR PARKED AIRCRAFT

Damage type	Nature of damage	Overpressure	
			psi
Severe	Major (or depot level) maintenance required to restore aircraft to operational status.	Transport airplanes	3
		Light liaison craft	2
		Helicopters	3
Moderate	Field maintenance required to restore aircraft to operational status.	Transport airplanes	2
		Light liaison craft	1
		Helicopters	1.5
Light	Flight of the aircraft not prevented, although performance may be restricted.	Transport airplanes	1
		Light liaison craft	0.5
		Helicopters	0.5

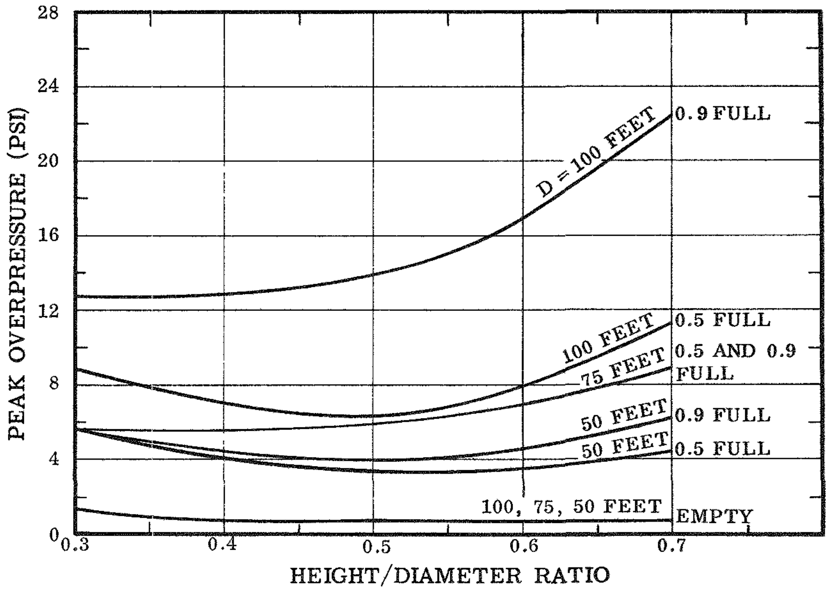

Figure 4.57a. Peak overpressures for severe blast damage to floating- or conical-roof tanks for explosions from 1 to 500 kilotons.

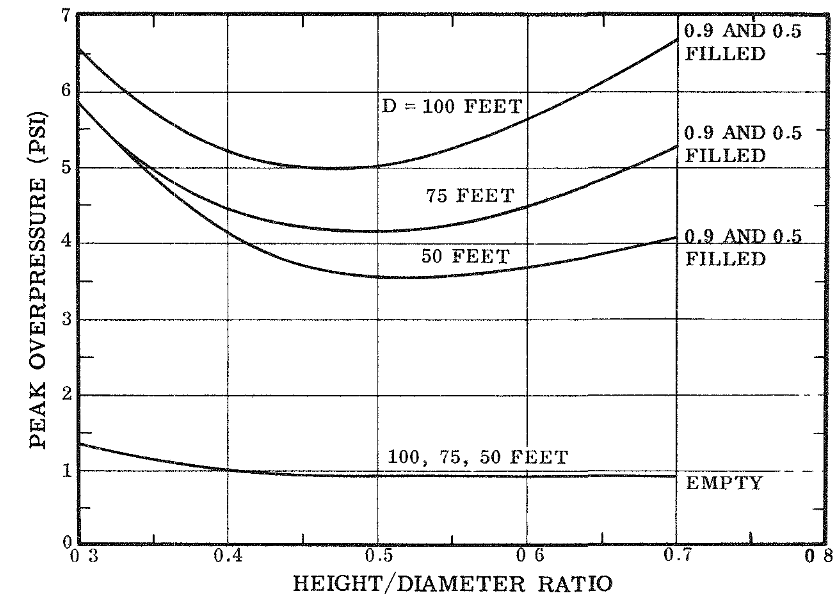

Figure 4.57b. Peak overpressures for severe blast damage to floating- or conical-roof tanks from explosions of 500 kilotons or more.

TYPES OF STRUCTURES

1. Wood-frame building.
2. Multistory, wall-bearing buildings, brick apartment house type.
3. Multistory, wall-bearing buildings, monumental type.
4. Multistory, blast-resistant design, reinforced-concrete buildings.
5. Multistory, reinforced-concrete buildings, with concrete walls and small window area.
6. Highway truss bridges of 150 to 250 foot span (blast normal to longitudinal bridge axis).
7. Multistory, reinforced-concrete, frame office type buildings, earthquake resistant.
8. Light steel-frame industrial buildings.
9. Heavy steel-frame industrial buildings (25 to 50 ton crane).
10. Heavy steel-frame industrial buildings (60 to 100 ton crane).
11. Railroad truss bridges of 150 to 250 foot span (blast normal to longitudinal bridge axis).
12. Multistory, reinforced-concrete frame office type buildings.
13. Highway and railroad truss bridges of 250 to 400 foot spans (blast normal to longitudinal bridge axis).
14. Multistory, steel-frame office type buildings.
15. Multistory, steel-frame office type buildings, earthquake resistant.

For a surface burst multiply the range by three-quarters.

Example:

Given: Wood-frame building (Type 1). A 1 MT weapon is burst (*a*) at the optimum height, (*b*) at the surface.

Find: The ranges from ground zero for severe and moderate damage.

Solution: (*a*) From the point 1 (at the right) draw a straight line to 1 MT on the severe damage scale and another to 1 MT on the moderate damage scale. The intersections of these lines with the range scale give the required solutions for the optimum burst height; thus,

Range for severe damage = 29,000 feet. *Answer.*

Range for moderate damage = 34,000 feet. *Answer.*

(*b*) For a surface burst the respective ranges are three-quarters those obtained above; hence,

Range for severe damage = 22,000 feet. *Answer.*

Range for moderate damage = 26,000 feet. *Answer.*

(The values have been rounded off to two significant figures, since greater precision is not warranted.)

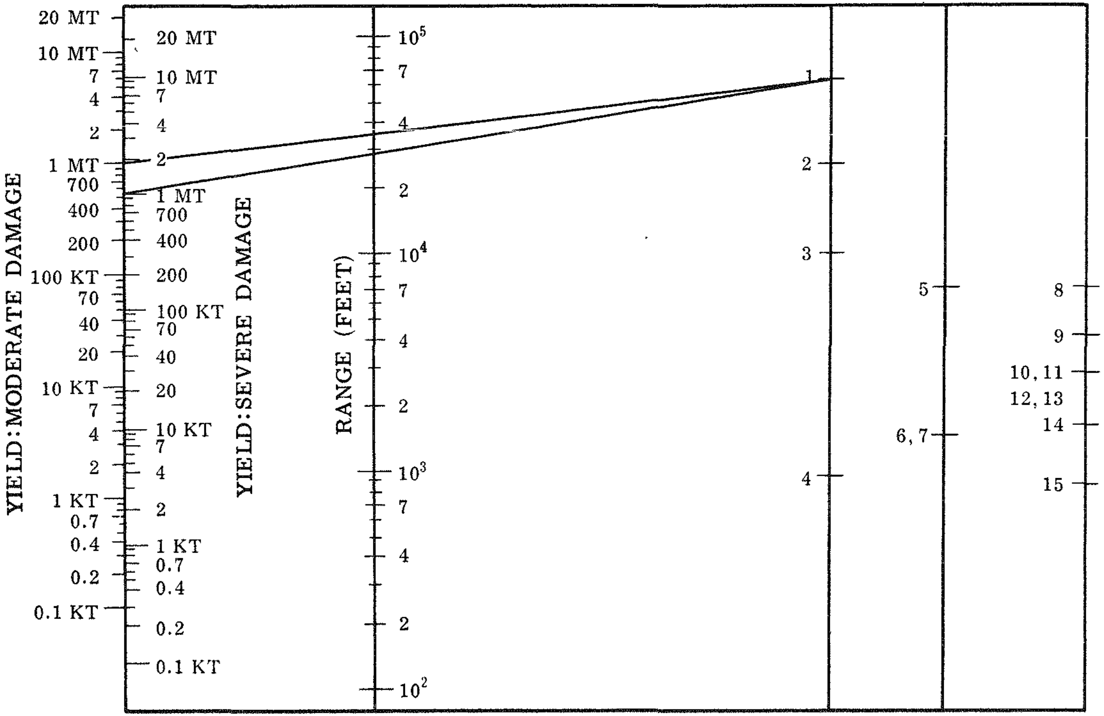

Figure 4.58a. Damage-distance relationships for structures of various types.

Targets

1. Truck mounted engineering equipment (unprotected).
2. Earth moving engineering equipment (unprotected).
3. Transportation vehicles.
4. Boxcars, flatcars, full tank cars, and gondola cars (side-on orientation).
5. Locomotives (side-on orientation).
6. Telephone lines (radial).
7. Telephone lines (transverse).
8. Average forest stand.
9. Boxcars, flatcars, full tank cars, and gondola cars (end-on orientation).
10. Locomotives (end-on orientation).
11. Merchant shipping.

Subscript "m" refers to moderate damage and subscript "s" refers to severe damage.

For a surface burst multiply the range by three-quarters for Items 1 through 8. For Items 9, 10, and 11, the ranges are the same for a surface burst as for the optimum burst height.

Example:

Given: A transportation type vehicle (Item 3). A 10 KT weapon is burst at (*a*) the optimum height, (*b*) at the surface.

Find: The range from ground zero for severe and moderate damage.

Solution: (*a*) Draw straight lines from the points 3_s and 3_m, at the right, to 10 KT on the yield scale at the left. The intersection of these lines with the range scale give the solutions for severe and moderate damage, respectively, for the optimum burst height; thus,

Range for severe damage=1,900 feet. *Answer.*

Range for moderate damage=2,900 feet. *Answer.*

(*b*) For a surface burst the ranges in this case are three-quarters those obtained above, thus,

Range for severe damage=1,400 feet. *Answer.*

Range for moderate damage=2,200 feet. *Answer.*

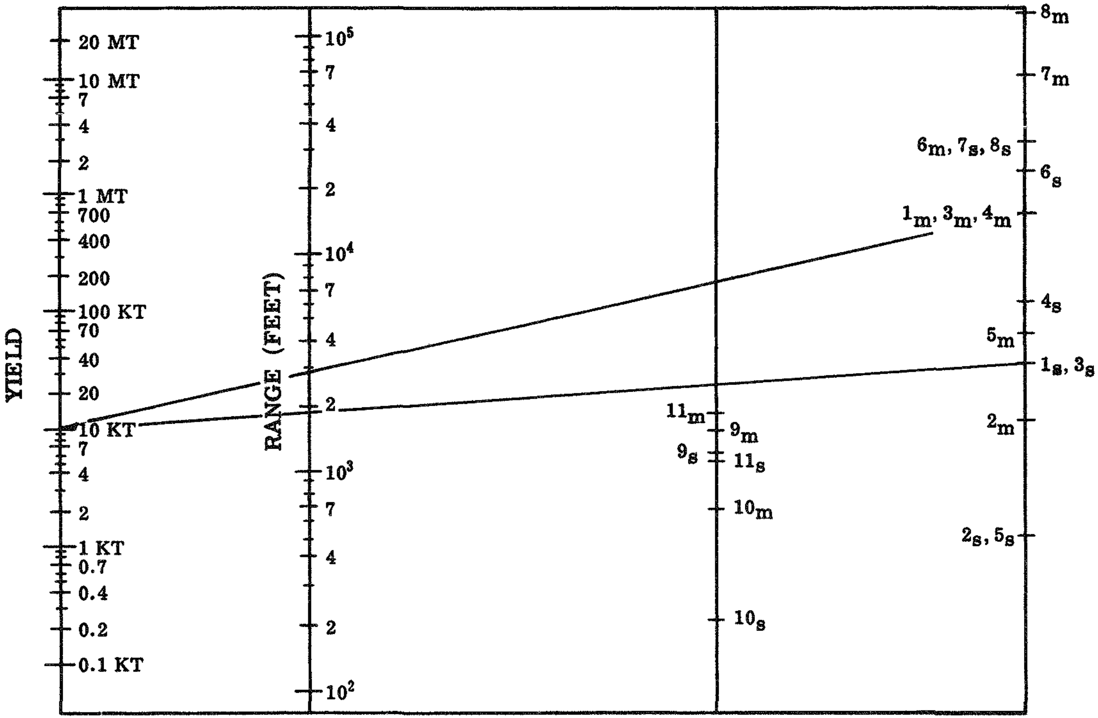

Figure 4.58b. Damage-distance relationships for various targets.

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*These documents may be obtained for a small charge from the Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C.

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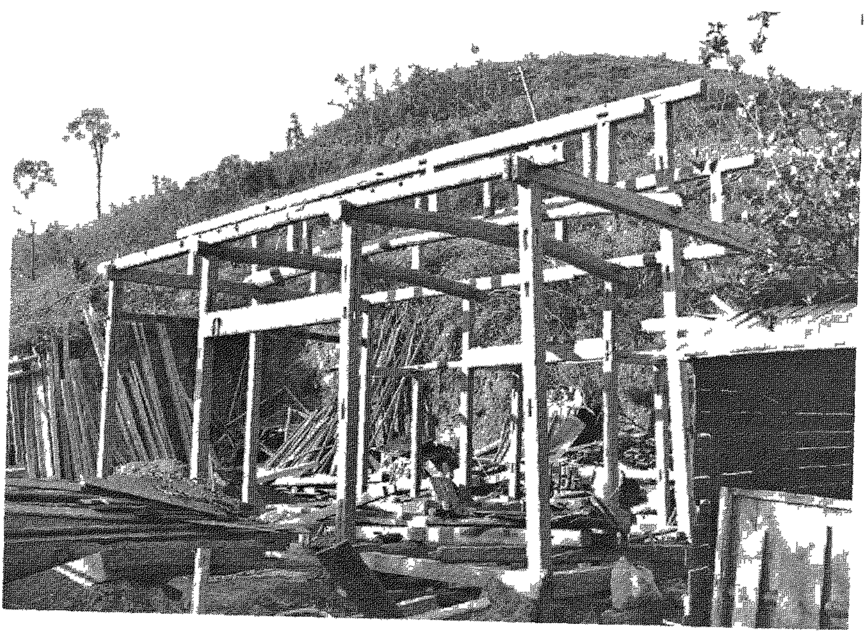

Figure 5 08 Upper photo Wood-frame building, 1 0 mile from ground zero at Hiroshima Lower photo Frame of residence under construction, showing small tenons

Two-Story, Brick-Wall-Bearing House

5.29 For comparison with the tests on the two-story wood frame structures, made in 1953, two brick-wall-bearing houses of conventional construction, similar in size and layout, were exposed to 5 and 1.7 pounds per square inch overpressure, respectively, in the 1955 tests (Fig. 5.29). The exterior walls were of brick veneer and cinder block and the foundation walls of cinder block; the floors, partitions, and roof were wood-framed.

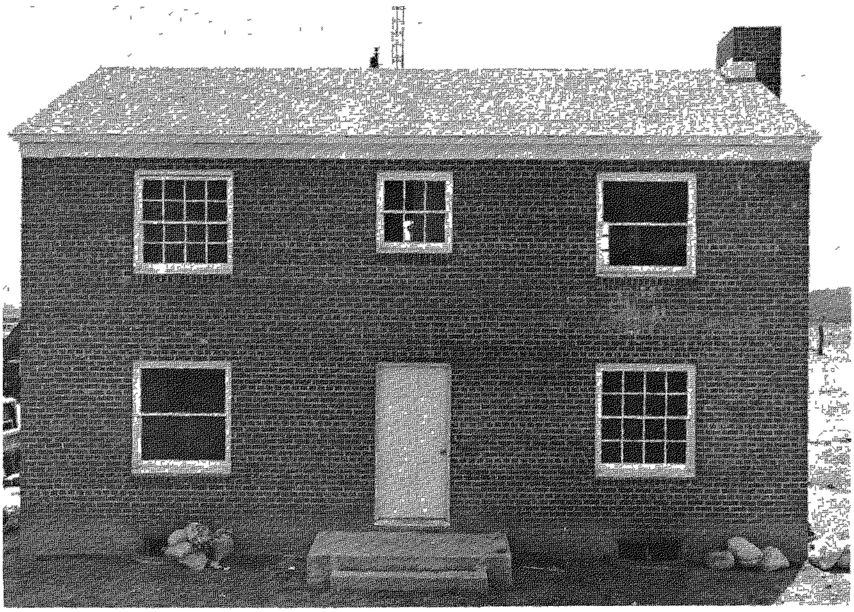

Figure 5.29. Unreinforced brick house before a nuclear explosion, Nevada Test Site.

5.30 At an incident overpressure of 5 pounds per square inch, the brick-wall house was damaged beyond repair (Fig. 5.30). The exterior walls were exploded outward, so that very little masonry debris fell on the floor framing. The roof was demolished and blown off, the rear part landing 50 feet behind the house. The first floor had partially collapsed into the basement as a result of fracturing of the floor joists at the center of the spans and the load of the second floor which fell upon it. The chimney was broken into several large sections.

Figure 5 30 Unreinforced brick house after a nuclear explosion (5 psi over pressure)

Figure 5 31 Unreinforced brick house after a nuclear explosion (1 7 psi overpressure)

5.31 Farther from the explosion, where the overpressure was 1.7 pounds per square inch, the corresponding structure was damaged to a considerable extent. Nevertheless, its condition was such that it could be made available for habitation by shoring and some fairly inexpensive repairs (Fig. 5.31).

5.32 There was no apparent damage to the masonry of the house, but the roof and second-floor ceiling framing suffered badly. The connections to the rear rafters at the ridge failed and the rafters dropped several inches. The ridge was split in the center portion and some of the 2 x 4-inch collar beams were broken in half. The ceiling joists at the rear were split in midspan, and the lath and plaster ceiling was blown downward. The second-floor framing was not appreciably affected and only a few of the first-floor joists were fractured. The interior plastered wall and ceiling finish were badly damaged.

5.33 The glass in the front and side windows was blown in, but the rear windows suffered much less. The exterior doors were demolished and several interior bedroom and closet doors were blown off their hinges.

One-Story, Wood-Frame (Rambler Type) House

5.34 A pair of the so-called "rambler" type, single-story, wood-frame houses were erected on concrete slabs poured in place, at grade. They were of conventional design except that each contained a shelter, above ground, consisting of the bathroom walls, floor, and ceiling of reinforced concrete with blast-door and shutter (Fig. 5.34).

5.35 When exposed to an incident overpressure of about 5 pounds per square inch, one of these houses was demolished beyond repair. However, the bathroom shelter was not damaged at all. Although the latch bolt on the blast shutter failed, leaving the shutter unfastened, the window was found to be still intact. The roof was blown off and the rafters were split and broken. The side walls at gable ends were blown outward, and fell to the ground. A portion of the front wall remained standing, although it was leaning away from the direction of the explosion (Fig. 5.35).

5.36 The other house of the same type, subjected to a peak overpressure of 1.7 pounds per square inch, did not suffer too badly, and it could easily have been made habitable. Windows were broken, doors blown off their hinges, and plaster-board walls and ceilings were badly damaged. The main structural damage was a broken midspan rafter support beam and wracking of the frame. In addition, the porch roof was lifted 6 inches off its supports.

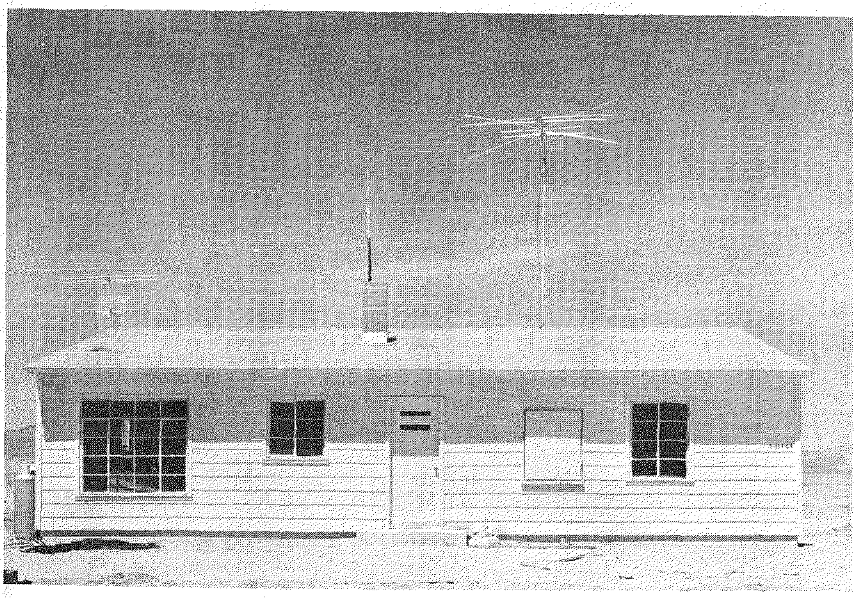

Figure 5.34. Rambler-type house before a nuclear explosion, Nevada Test Site. (Note blast door over bathroom window at right.)

Figure 5.35. Rambler-type house after a nuclear explosion (5 psi overpressure).

722-454 O - 64 - 15

ONE-STORY, PRECAST CONCRETE HOUSE

5.37 Another residential type of construction tested in 1955 was a single-story house made of precast, light weight (expanded shale aggregate) concrete wall and partition panels, joined by welded matching steel lugs. Similar roof panels were anchored to the walls by special countersunk and grouted connections. The walls were supported on concrete piers and a concrete floor slab, poured in place on a tamped fill after the walls were erected. The floor was anchored securely to the walls by means of perimeter reinforcing rods held by hook bolts screwed into inserts in the wall panels. The overall design was such as to comply with the California code for earthquake-resistant construction (Fig. 5.37).

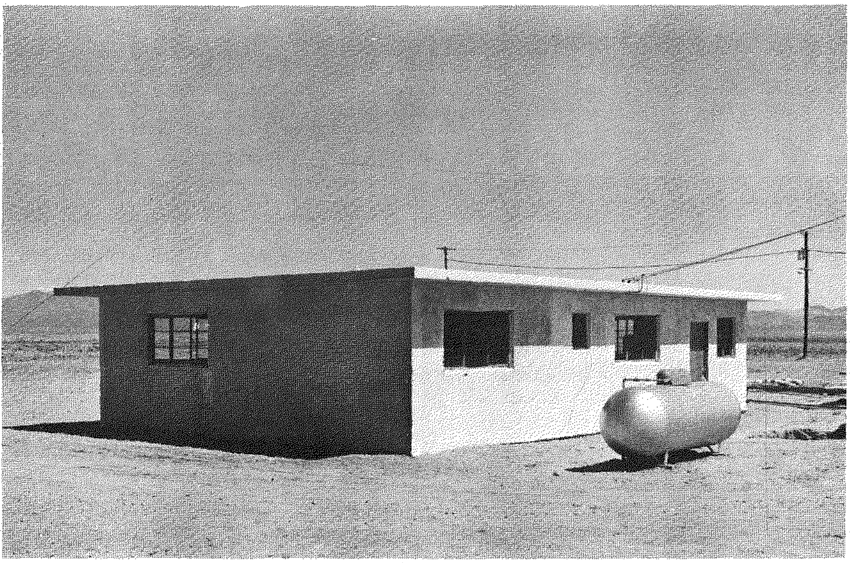

Figure 5.37. Reinforced precast concrete house before a nuclear explosion, Nevada Test Site.

5.38 This house stood up well, even at a peak overpressure of 5 pounds per square inch. By replacement of demolished or badly damaged doors and windows, it could have been made available for occupancy (Fig 5.38).

5.39 There was some indication that the roof slabs at the front of the house were lifted slightly from their supports, but this was not sufficient to break any connections. Some of the walls were cracked

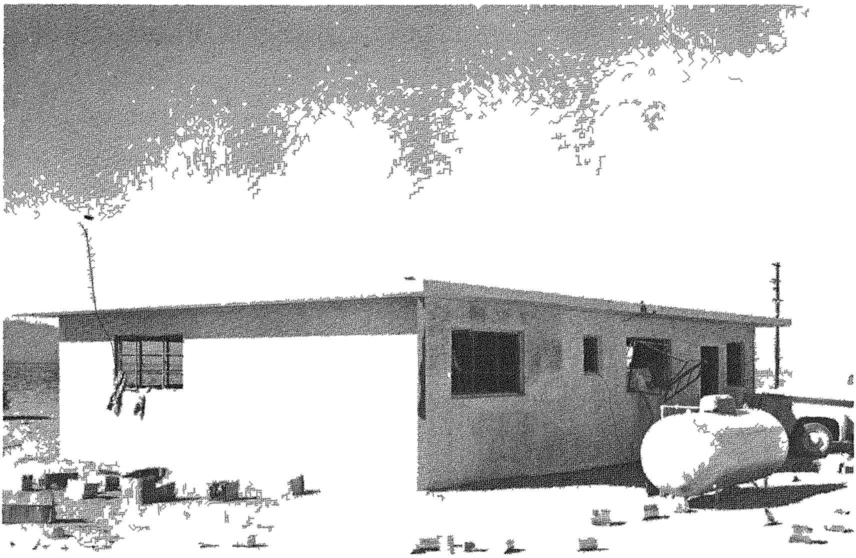

Figure 5 38 Reinforced precast concrete house after a nuclear explosion (5 psi overpressure). The LP-gas tank, sheltered by the house, is essentially undamaged

slightly and others showed indications of minor movement. In certain areas the concrete around the slab connections was spalled, so that the connectors were exposed The steel window-sashes were somewhat distorted, but they remained in place.

5.40 As may be expected from what has been just stated, the precast concrete-slab house suffered relatively minor damage at 1 7 pounds per square inch peak overpressure. Glass was broken extensively, and doors were blown off their hinges and demolished, as in other houses exposed to the same air pressure. But, apart from this and distortion of the steel window sash, the only important damage was spalling of the concrete at the lug connections

One-Story, Reinforced-Masonry House

5.41 The last type of house subjected to test in 1955 was also of earthquake-resistant design. The floor was a concrete slab, poured in place at grade. The walls and partitions were built of lightweight (expanded shale aggregate) 8-inch masonry blocks, reinforced with vertical steel rods anchored into the floor slab. The walls were also

reinforced with horizontal steel rods at two levels, and openings were spanned by reinforced lintel courses. The roof was made of precast, lightweight concrete slabs, similar to those used in the precast concrete houses described above (Fig. 5.41).

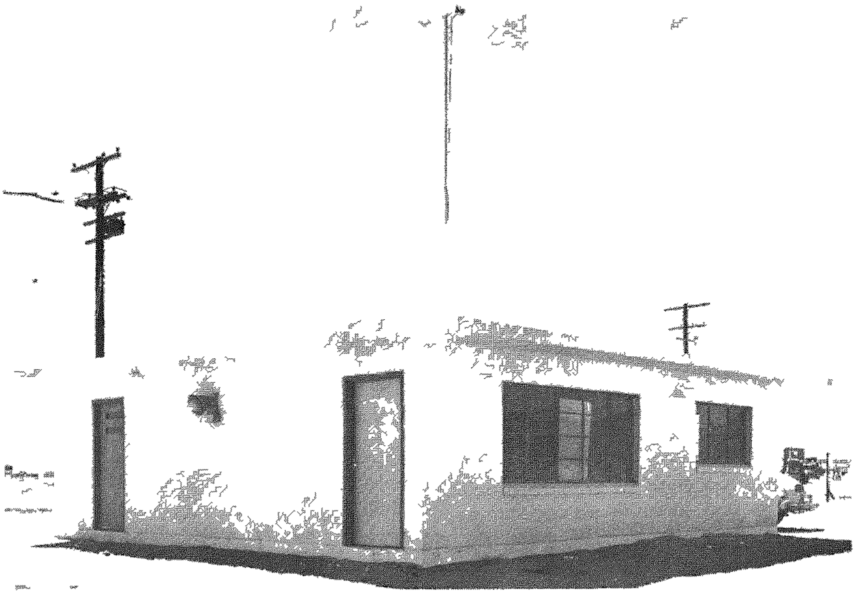

Figure 5 41 Reinforced masonry-block house before a nuclear explosion, Nevada Test Site

5.42 At a peak overpressure of about 5 pounds per square inch, windows were destroyed and doors blown in and demolished. The steel window-frames were distorted, although nearly all remained in place. The house suffered only minor structural damage and could have been made habitable at relatively small cost (Fig. 5.42).

5.43 There was some evidence that the roof slabs had been moved, but not sufficiently to break any connections. The masonry wall under the large window (see Fig. 5 42) was pushed in about 4 inches on the concrete floor slab; this appeared to be due to the omission of dowels between the walls and the floor beneath window openings. Some cracks developed in the wall above the same window, probably as a result of improper installation of the reinforced lintel course and the substitution of a pipe column in the center span of the window.

5.44 A house of the same type exposed to the blast at a peak overpressure of 1.7 pounds per square inch suffered little more than

the usual destruction of doors and windows. The steel window-sash remained in place but was distorted, and some spalling of the concrete around lug connections was noted. On the whole, the damage to the house was of a minor character and it could readily have been repaired.

Trailer-Coach Mobile Homes

5.45 Sixteen trailer coaches of various makes, intended for use as mobile homes, were subjected to blast in the 1955 test. Trailer parks and dealer stocks are generally situated at the outskirts of cities, and so the mobile homes to be tested were placed at a considerable distance from ground zero. Nine trailer-coach mobile homes were located where the peak blast overpressure was 1.7 pounds per square inch, and the other seven where the overpressure was about 1 pound per square inch. They were parked at various angles with respect to the direction of travel of the blast wave.

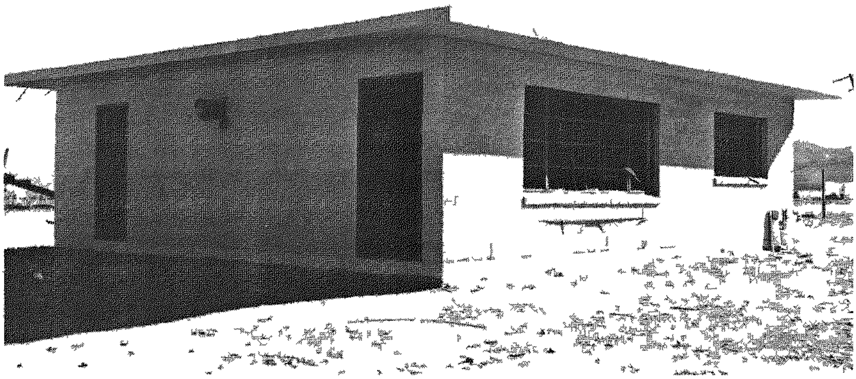

Figure 5.42 Reinforced masonry-block house after a nuclear explosion (5 psi overpressure)

5.46 At the higher overpressure two of the mobile homes were tipped over by the explosion. One of these was originally broadside

to the blast, whereas the second, at an angle of about 45°, was of much lighter weight. All the others at both locations remained standing. On the whole, the damage sustained was not of a serious character. There were variations from one trailer-coach to another subjected to the same blast pressure, because of different methods of construction, types of fastening, gage and design of die-formed metal, spacing of studs, and window sizes.

5.47 From the exterior, many of the mobile homes showed some dents in walls or roof, and a certain amount of distortion. There were, however, relatively few ruptures. Most windows were broken, but there was little or no glass in the interior, especially in those coaches having screens fitted on the inside. Where there were no screens or venetian blinds, and particularly where there were large picture windows, glass was found inside.

5.48 The interiors of the mobile homes were usually in a state of disorder due to ruptured panels, broken and upset furniture, and cupboards, cabinets, and wardrobes which had been torn loose and damaged. Stoves, refrigerators, and heaters were not displaced, and the floors were apparently unharmed. The plumbing was, in general, still operable after the explosion. Consequently, by rearranging the displaced furniture, repairing cabinets, improvising window coverings, and cleaning up the debris, all trailer-coaches could have been made habitable for emergency use.

5.49 At the 1 pound per square inch overpressure location some windows were broken, but no major damage was sustained. The principal repairs required to make the mobile homes available for occupancy would be window replacement or improvised window covering.

Food Products

5.50 To determine the effects of a nuclear explosion on foodstuffs, some 90 food products were exposed in the 1955 tests. The selection was based on an evaluation of the American diet, so as to insure the inclusion of items which were used either most frequently or in largest volume. About half of the products were staples, e.g., flour and sugar; semi-perishables, e.g., potatoes, fruits, and processed meats; and perishables, e.g., fresh meats and frozen foods. The other half consisted of heat-sterilized foods canned in metal or glass containers. In addition to the extensive variety of foodstuffs, a number of different kinds of retail and wholesale packaging materials and methods were tested.

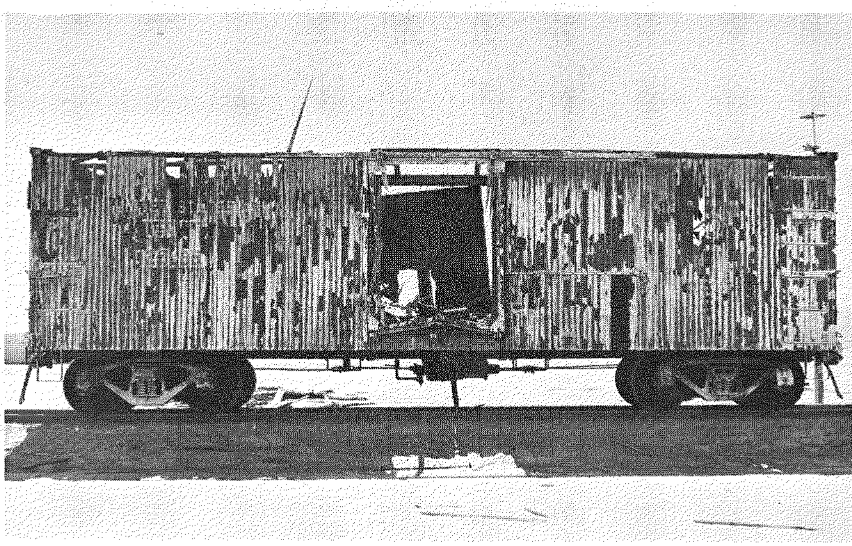

Figure 5.101a. Loaded wooden boxcar after a nuclear explosion (4 psi overpressure).

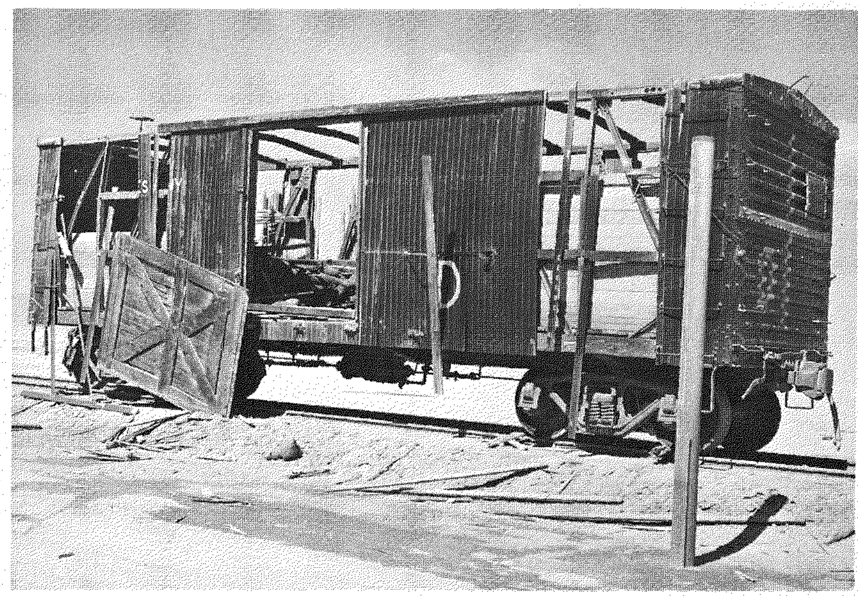

Figure 5.101b. Loaded wooden boxcar after a nuclear explosion (6 psi overpressure).

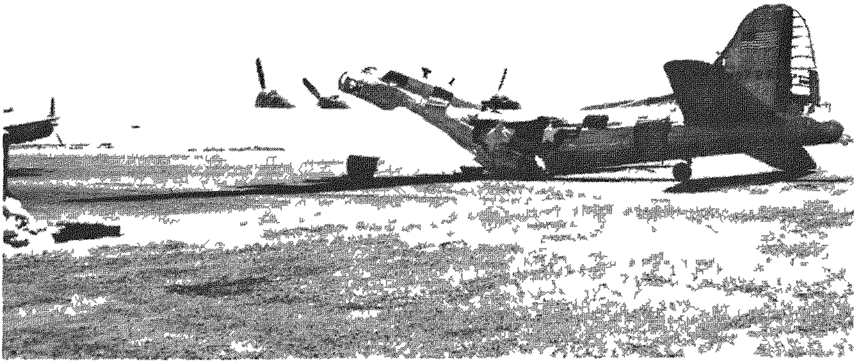

Figure 5.104a. Aircraft after side exposed to a nuclear explosion (3.6 psi overpressure).

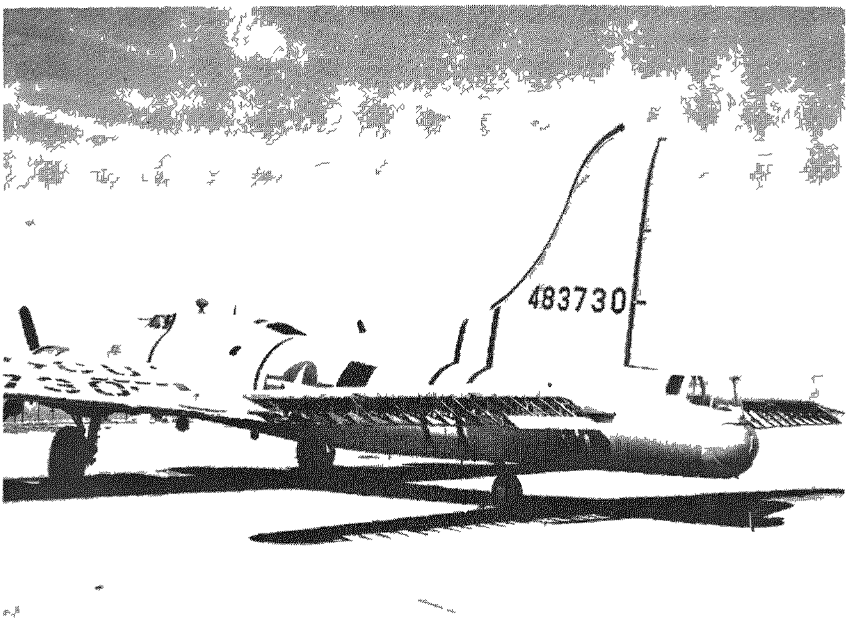

Figure 5.104b. Aircraft after tail exposed to a nuclear explosion (2 4 psi overpressure).

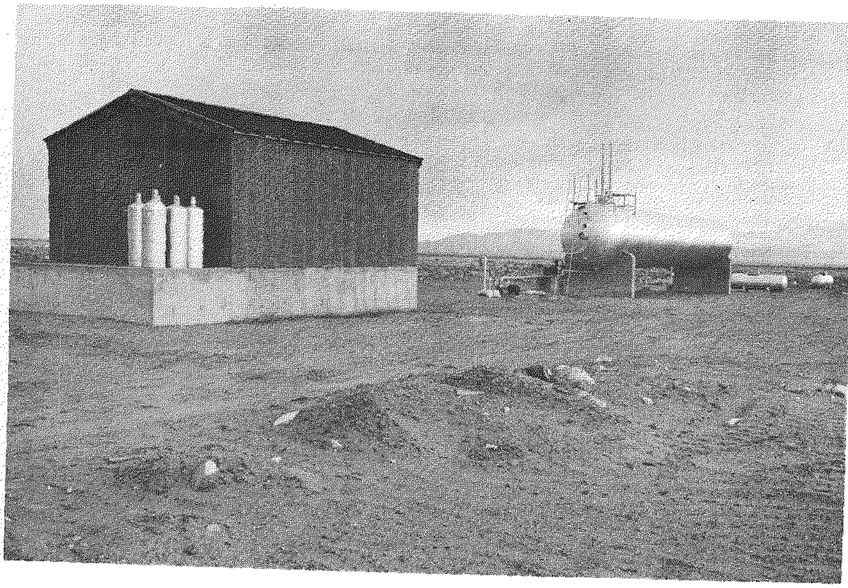

Figure 5.132. Upper photo: LP-gas bulk storage and filling plant before a nuclear explosion. Lower photo: The plant after the explosion (5 psi overpressure).

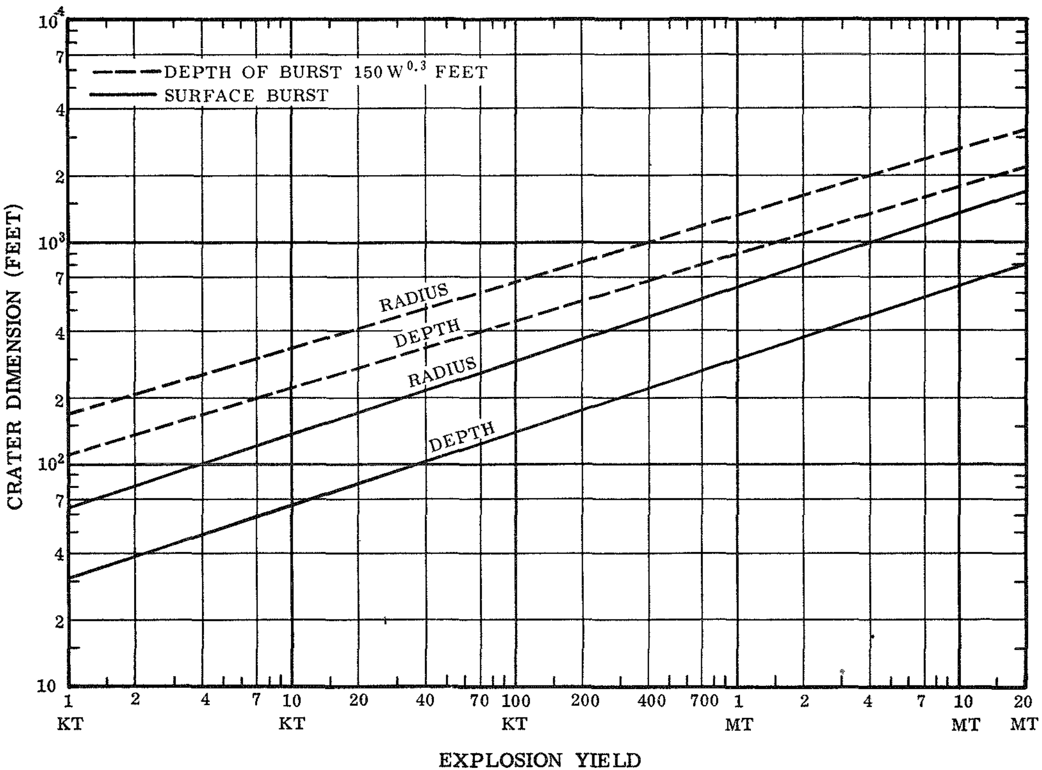

Figure 6.48. Apparent crater dimensions for bursts at the surface and at a depth of 150 $W^{0.3}$ feet in dry soil.

6.69 The shock parameter mainly responsible for damage has not been defined either theoretically or empirically. However, there is considerable evidence that the degrees of damage can be related, without serious error, to the apparent crater radius. Some examples of this type of relationship are given in Table 6.69 for moderately deep underground structures, defined as structures located such that the ratio of the depth of cover at the crown to the span is greater than unity. There are certain minor variations in the distances due to the factors referred to in § 6.22, as well as to the characteristics of the soil or rock in which the structure is buried. It will be seen that, as is to be anticipated, there is no damage from ground shock beyond the plastic zone, i.e., farther than about two and one-half (apparent) crater radii from surface zero.

TABLE 6.69

DAMAGE CRITERIA FOR MODERATELY DEEP UNDERGROUND STRUCTURES

Structural type	Damage type	Distance from surface zero	Nature of damage
Relatively small, heavy well-designed underground structures.	Severe	1¼ apparent crater radii	Collapse.
	Light	2½ apparent crater radii	Slight cracking, severance of brittle external connections.
Relatively long, flexible structures, e.g., buried pipelines, tanks, etc.	Severe	1½ apparent crater radii	Deformation and rupture.
	Moderate	2 apparent crater radii	Slight deformation and rupture.
	Light	2½ to 3 apparent crater radii	Failure of connections.

6.70 Although tunnels and subways would be destroyed within the crater region and would suffer damage outside this area, these structures, especially when bored through solid rock and lined to minimize spalling, are very resistant to ground shock. The rock, being an elastic medium, will transmit the pressure (compression) wave very well, and when this wave strikes the wall of the tunnel, a tensile (negative pressure) wave is reflected from the rock-air interface.[2] Even in a soil medium, tunnels and subways could survive; flexible structures would resist damage by taking advantage of the tremendous passive earth pressure. However, construction in soil should be above the water table, if possible.

6.71 Under certain circumstances, failure of the rock at the tunnel wall will result in spalling when the reflected tensile stress exceeds the tensile strength of the rock. The thickness of spalling

[2] The formation of a negative pressure wave upon reflection of a compression wave at the surface of a less dense medium (air) is discussed more fully in the treatment of shock waves in water (§ 6.28).

is dependent upon the magnitude, duration, and shape of the pressure wave, upon the size and shape of the tunnel, and upon the physical properties of the rock.

6.72 When structures are partly above and partly below ground, the damage to the underground portion will be very much as indicated in Table 6.69, if the walls are sufficiently strong. However, as a general rule, for surface and subsurface bursts, destruction due to air blast will extend well beyond the plastic zone, the third region referred to earlier. The overall damage is then determined by the air blast, and is in accordance with the discussion in Chapter IV.

TECHNICAL ASPECTS OF UNDERWATER EXPLOSIONS

Shock Wave Properties

6.73 By combining a theoretical treatment with measurements made in connection with detonations of TNT charges under water, some characteristic properties of the underwater shock from a nuclear explosion have been calculated. The peak pressure, the impulse per unit area, and the energy per unit area of the shock wave at various distances from a deep underwater explosion of 1-kiloton energy, are recorded in Fig. 6.73. An explosion at a considerable depth in deep water is postulated, so as to eliminate the effects of surfaces. Consequently, the values of impulse given in Fig. 6.73 are independent of the cutoff effect. For an explosion and target near the surface, the impulse and energy would be greatly decreased.

6.74 The scaling procedures for calculating water shock wave properties for an explosion of W kilotons yield are similar to those described in Chapter III for an air burst. Thus, if D_1 is the slant distance from a 1-kiloton explosion under water at which a certain shock pressure occurs, then for a W-kiloton burst the same pressure will be attained at a slant distance D, where

$$D = D_1 \times W^{1/3},$$

as in equation (3.56.2) for an air burst. The underwater impulse and energy scale in the same manner as impulse for an explosion in the air, as given in § 3.58. Thus,

$$I = I_1 \times W^{1/3} \text{ at a distance } D = D_1 \times W^{1/3},$$

$$E = E_1 \times W^{1/3} \text{ at a distance } D = D_1 \times W^{1/3},$$

where I and E are the impulse and energy, respectively, at a distance D from an explosion of W kilotons, and I_1 and E_1 are the values at a distance D_1 from a 1-kiloton explosion. These scaling laws are illustrated in connection with the example based on the use of Fig. 6.73.

(Text continued on p. 303.)

The curves in Fig. 6.73 show the peak water overpressure, the energy per unit area, the impulse per unit area, and the time constant (defined in § 6.75) as a function of distance (slant range) from a 1-kiloton explosion in deep water.

Scaling. For yields other than 1 KT, the range to which a given pressure extends is given by

$$D=D_1\times W^{1/3},$$

where D_1 is the distance from the explosion for 1 KT and D is the distance from the explosion for W KT.

For the impulse, energy, and time constant the appropriate scaling equations are as follows:

$$I=I_1\times W^{1/3} \text{ at } D=D_1\times W^{1/3},$$

$$E=E_1\times W^{1/3} \text{ at } D=D_1\times W^{1/3},$$

and

$$\theta=\theta_1\times W^{1/3} \text{ at } D=D_1\times W^{1/3},$$

where I_1, E_1, θ_1 are impulse, energy, and time constant for 1 KT at distance D_1, and I, E, and θ are impulse, energy, and time constant for W KT at distance D.

Example

Given: A 30 KT weapon detonated in deep water.

Find: The peak overpressure, impulse, energy, and time constant at a slant range of 3.1 miles.

Solution: The distance D_1 for 1 KT, corresponding to $D=3.1$ miles for 30 KT, is $3.1/30^{1/3}=3.1/3.1=1$ mile. From Fig. 6.73, the peak overpressure at 1 mile from a 1 KT burst is 330 psi. By the scaling law, the same pressure occurs at a distance $1\times30^{1/3}=3.1$ miles from a 30 KT explosion; hence, the required value of the peak overpressure is 330 psi. *Answer.*

At 1 mile from the 1 KT explosion, the impulse, energy, and time constant from Fig. 6.73 are as follows:

Impulse=6.5 lb-sec/in^2
Energy=12.5 lb-ft/in^2
Time constant=17.3 millisec.

Therefore, at 3.1 miles from the 30 KT burst, the corresponding values will be

Impulse$=6.5\times30^{1/3}=20.2$ lb-sec/in^2
Energy$=12.5\times30^{1/3}=39$ lb-ft/in^2
Time constant$=17.5\times30^{1/3}=54$ millisec. *Answer.*

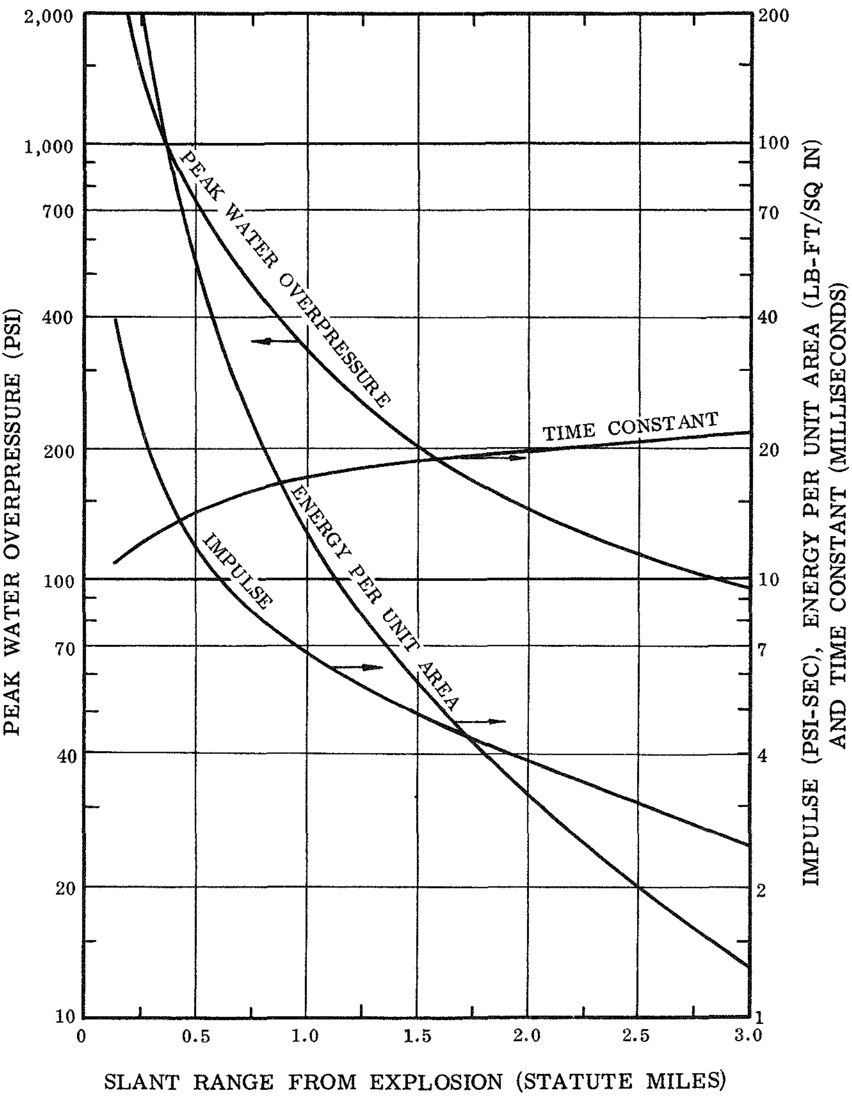

Figure 6 73. Water shock wave properties for a 1-kiloton explosion in deep water.

(Text continued from p. 301.)

6.75 The rate at which the shock pressure, at a fixed distance from the explosion, falls off with time can be represented by

$$p(t)=pe^{-t/\theta}, \qquad (6.75.1)$$

where $p(t)$ is the pressure at a time t after the arrival of the shock front at the point of observation, p is the peak value at the time of

arrival, and θ is a parameter called the "time constant." Physically, θ is the time at which the pressure has decayed to p/e. The time constant varies with the distance from the explosion, and some calculated values for a deep underwater explosion of 1-kiloton energy are included in Fig. 6.73. The time constant for an explosion of W-kilotons energy may be obtained by the scaling method given above for energy and impulse.

6.76 It is apparent from equation (6.75.1) that θ determines the rate at which the shock pressure decreases with time and, consequently, provides a relative indication of the duration of the shock wave. As θ increases with increasing distance from the explosion, the duration of the shock wave increases correspondingly.

6.77 The peak pressure and duration of the water shock wave from a burst in shallow water will be less than those given above for an explosion in deep water, because of the influence of the air and bottom boundaries. The peak water pressures versus distances from surface zero for a 1-kiloton burst at mid-depth, as derived from measurements made at the Bikini BAKER test, are shown in Fig. 6.77. The results are applicable, in general, to a burst at mid-depth in water having a scaled total depth, i.e., actual depth divided by $W^{1/3}$, of 66 feet. The distance at which a given peak pressure occurs is then obtained upon multiplying by the usual scaling factor of $W^{1/3}$.

Air Blast from Underwater Explosions

6.78 As seen earlier, a certain amount of the shock energy accompanying a shallow underwater explosion is transmitted as a blast wave in the air. The proportion of the energy so transmitted depends upon the depth of burst, but in order to give some indication of the overpressures in the air, the data obtained at the Bikini BAKER test have been used as a basis. From these, with the aid of the familiar $W^{1/3}$ scaling law, the curve in Fig. 6.78 has been derived for a 1-kiloton underwater explosion. The overpressures obtained from this curve will be lower than observed from a surface burst, but greater than those from a deeper burst in water. As a rough approximation, this overpressure-distance curve may be used, together with the usual scaling law for blast overpressure, for any shallow burst in moderately deep water.

Wave Height in Underwater Explosions

6.79 By empirical analysis and appropriate scaling of the wave heights observed at various tests, a curve (Fig. 6.79) has been con-

structed for estimating maximum wave heights (crest to trough) at various distances from a 1-kiloton underwater burst. The results apply to an explosion of W-kilotons energy yield in water having a scaled depth of 85 feet, defined in this case as the actual water depth in feet divided by $W^{1/4}$. The wave height at any given distance from surface zero for a W-kiloton burst can be obtained upon multiplying the result for 1-kiloton yield in Fig. 6.79 by the scaling factor $W^{1/2}$. If the scaled depth of the water is less than 85 feet, the wave height is then directly proportional to the actual depth.

6.80 Experimental data from nuclear detonations in deep water are very limited. A curve based on theoretical considerations and the available measurements is included in Fig. 6.79; it gives a rough estimate of the maximum wave heights that could result from a 1-kiloton detonation in deep water, i.e., depth of water greater than 400 $W^{1/4}$ feet. Here also an approximate value of the wave height for a W-kiloton explosion can be obtained upon multiplying the result for 1-kiloton yield by the scaling factor $W^{1/2}$. It should be noted that the data in Fig. 6.79 are for a constant depth of water and, furthermore, they do not allow for peaking that may occur as the waves reach shallow water.

Underwater Crater Formation

6.81 The dimensions of the crater formed on the bottom as the result of an underwater explosion for a range of energy yields are represented by the curves in Fig. 6.81. The values are for a burst less than 15 feet deep and for one on the bottom in water 50 feet deep with sand, sand and gravel, or soft-rock bottom. The correction factors for other bottom materials are given on the page facing Fig. 6.81. Caution should be used in applying the results since the water action will cause the various dimensions, particulatly the lip height, to change quite rapidly.

DAMAGE FROM UNDERWATER SHOCK

Damage to Ships

6.82 A description of the interaction of underwater shock with ships, based on experience at the Bikini BAKER test, was given in § 6.35 *et seq.* For most cases of underwater explosions, the water

(Text continued on page 314.)

The curve in Fig. 6.77 shows the dependence of the peak wate overpressure on the distance (slant range) from the explosion for a 1 KT burst at mid-depth in water that is 66 feet deep.

Scaling. For a W KT burst, the distance at which a given pressure occurs in a scaled depth, i.e., actual depth divided by $W^{1/3}$, of 66 ft of water is obtained by multiplying the distance for a 1 KT explosion by $W^{1/3}$.

Example:

Given: A 30 KT weapon detonated at mid-depth in 200 feet of water.

Find: The distance at which a peak overpressure of 300 psi will occur.

Solution: The scaled depth corresponding to the actual depth of 200 feet is $200/30^{1/3}=200/3.1=65$ feet. This is close enough to 66 feet for Fig. 6.77 to be used.

From the curve, it is found that 300 psi occurs at 0.39 mile from a 1 KT explosion. Therefore, for a 30 KT weapon, the peak overpressure of 300 psi occurs at

$$0.39\times 30^{1/3}=0.39\times 3.1=1.2 \text{ miles.} \quad \textit{Answer.}$$

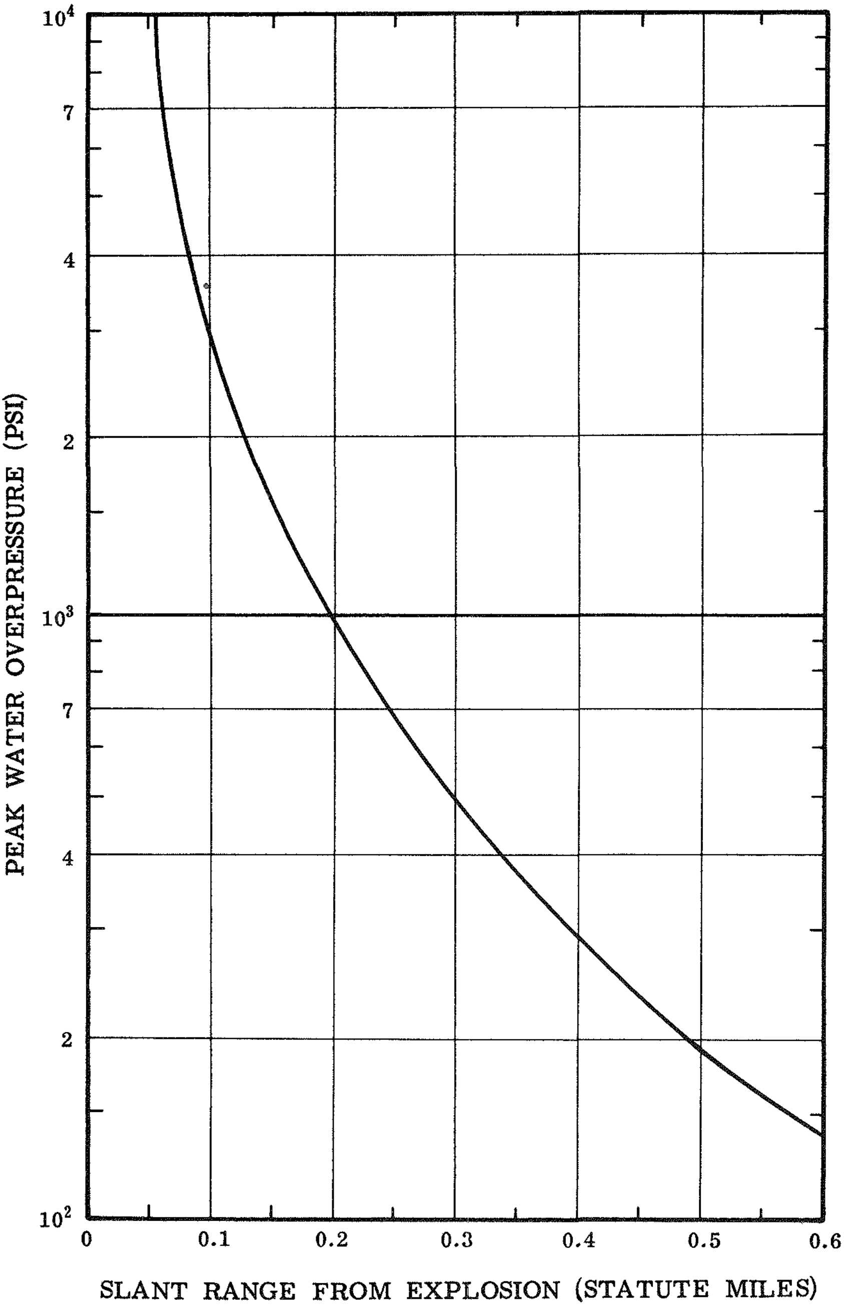

Figure 6.77. Peak water overpressure for a 1-kiloton explosion at mid-depth in water 66 feet deep.

The curve in Fig. 6.78 gives the peak air overpressure at the surface for a 1 KT explosion in shallow water as a function of the distance from surface zero.

Scaling. The distance at which a given peak air overpressure occurs for a W KT explosion is obtained by multiplying the distance for the same overpressure in the case of a 1 KT burst by the scaling factor $W^{1/3}$.

Example

Given: A 30 KT weapon detonated in 100 feet of water.

Find: The distance at which the air overpressure at the surface is 5 psi.

Solution: From Fig. 6.78, the air overpressure of 5 psi will occur at a distance of 0.2 mile from surface zero for a 1 KT burst. Hence, the surface zero distance from a 30 KT explosion for the same overpressure is

$$0.2 \times 30^{1/3} = 0.62 \text{ mile.} \quad \textit{Answer.}$$

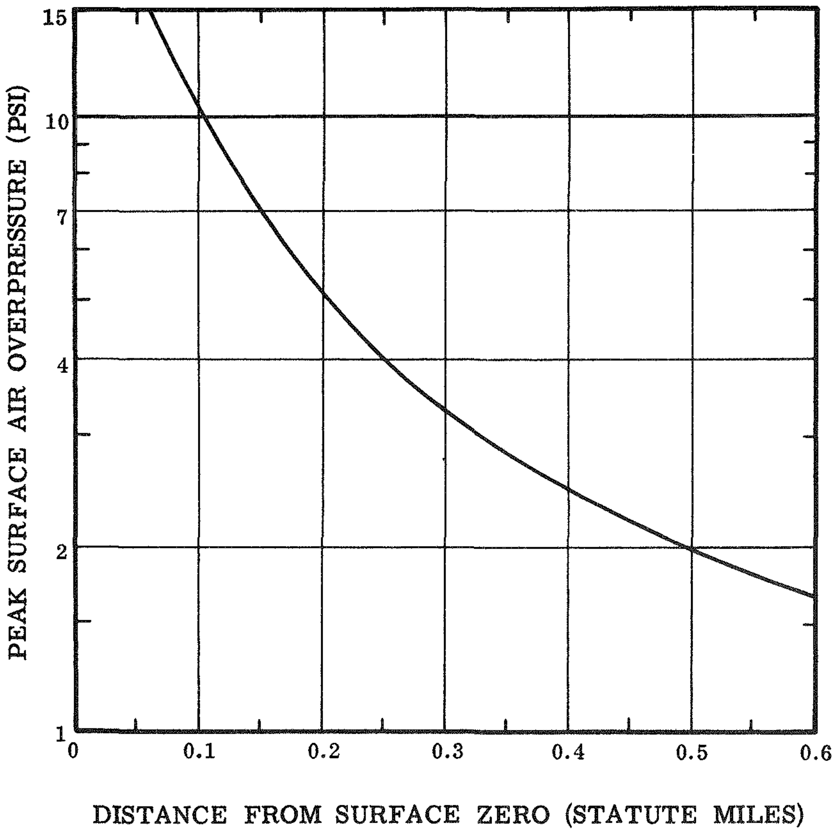

Figure 6.78. Peak air overpressure at surface for a 1-kiloton shallow underwater explosion.

The lower curve in Fig. 6.79 shows the approximate maximum crest-to-trough wave height versus horizontal surface distance for a 1 KT burst in water 85 feet deep. The upper curve is for a 1 KT burst in water more than 400 feet deep, so that the bottom does not affect the mechanism of wave formation.

Scaling. At a given distance from surface zero, the wave height for an explosion of W kilotons is $W^{1/2}$ times the wave height at this distance from a 1 KT burst in water of the same scaled depth, as obtained from Fig. 6.79. The scaled depth is $d/W^{1/4}$, where d is the actual depth in feet. For the lower curve in the figure the scaled depth is 85 feet and for the upper curve it is more than 400 feet.

For scaled water depths less than 85 feet, i.e., actual depths less than $85W^{1/4}$ feet, the estimated maximum wave height is proportional to the depth of water; thus,

$$h_d = h_{85}(d/W^{1/4}),$$

where h_d=wave height for any scaled water depth less than 85 feet, h_{85}=wave height for a scaled water depth of 85 feet obtained from Fig. 6.79, and d=depth of water in feet.

Example

Given: (*a*) A 30 KT weapon detonated in 200 feet of water.
(*b*) A 30 KT weapon detonated in 100 feet of water.
(*c*) A 30 KT weapon detonated in 1,000 feet of water.

Find: The expected maximum wave height in each case at 4 miles from surface zero.

Solution: (*a*) The scaled depth of the water is

$$200/30^{1/4} = 200/2.34 = 85 \text{ feet};$$

consequently, the lower curve in Fig. 6.79 is applicable to this case. From the curve, the maximum wave height at 4 miles from the 1 KT explosion is 1.0 feet. Therefore, for a 30 KT weapon in 200 feet of water, the wave height at 4 miles is

$$1.0 \times 30^{1/2} = 1.0 \times 5.5 = 5.5 \text{ feet, crest to trough.} \quad \textit{Answer.}$$

(*b*) Since 100 feet is less than $85W^{1/4}$ when W is 30 KT, the wave height will now be proportional to the actual depth of the water. When the depth is $85W^{1/4}$, i.e., 200 feet, the wave height at 4 miles from the 30 KT burst is 5.5 feet; hence, for a water depth of 100 feet the wave height at the same distance is

$$5.5 \times \frac{100}{200} = 2.7 \text{ feet, crest to trough.} \quad \textit{Answer.}$$

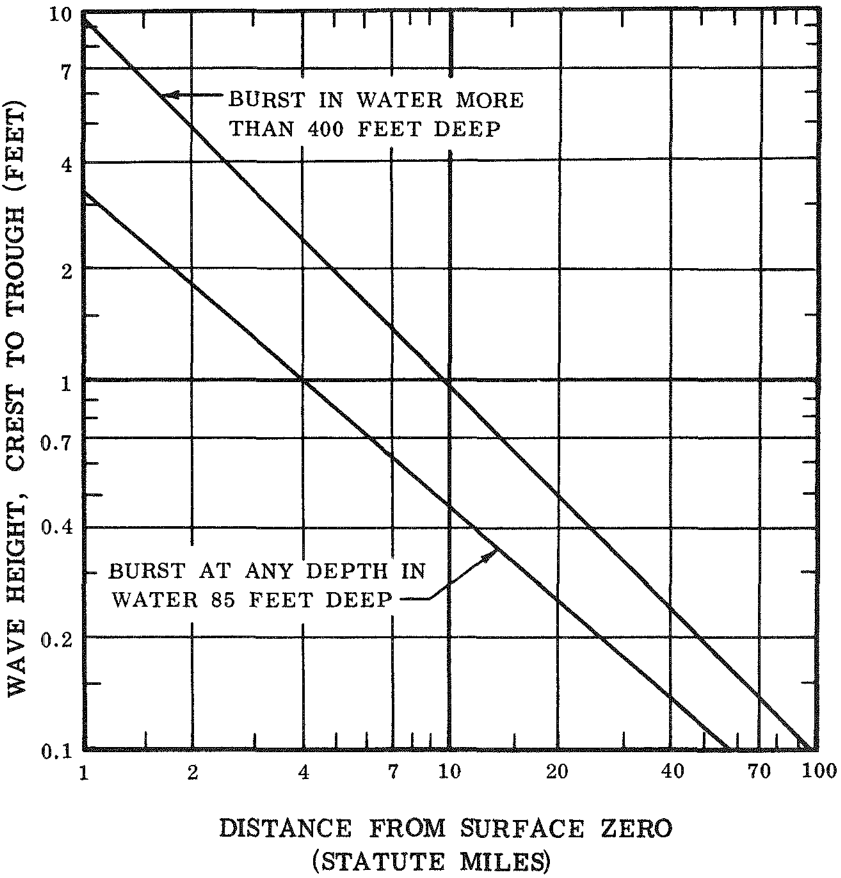

Figure 6.79. Maximum wave height in different types of 1-kiloton underwater bursts.

(*c*) The scaled depth of the water is

$$1{,}000/30^{1/4}=1{,}000/2.34=427 \text{ feet,}$$

and since this is greater than 400 feet, the upper curve in Fig. 6.79 must be used. From the curve, the maximum wave height at 4 miles from a 1 KT explosion is 2.4 feet. Therefore, for a 30 KT weapon detonated (at the proper depth) in 1,000 feet of water, the maximum wave height at 4 miles is

$$2.4\times30^{1/2}=2.4\times5.5=13 \text{ feet, crest to trough.} \quad \textit{Answer.}$$

The curves in Fig. 6.81 give the depth, diameter, and lip height of the underwater crater as functions of yield. The results are for a burst less than 15 feet deep and for one on the bottom in 50 feet of water for a sand, sand and gravel, or soft rock bottom.

For other bottom materials the crater dimensions can be estimated by multiplying the values from Fig. 6.81 by the following factors:

Material	*Diameter*	*Depth*	*Lip Height*
Loess	1.0	1.7	0.7
Clay	1.0	2.3	2.3
Hard rock	0.7	0.5	0.4
Mud or muck	0.7	0.4	0.2

Example

Given: A 200 KT weapon detonated in 50 feet of water; the bottom is predominantly clay.

Find: (*a*) The crater dimensions when the detonation is near the surface of the water.

(*b*) The crater dimensions when the detonation occurs on the bottom.

Solution: From Fig. 6.81, the crater dimensions for a 200 KT explosion are as follows:

	(*a*) *Feet*	(*b*) *Feet*
Diameter	1,000	1,900
Depth	44	120
Lip height	2.4	14

For a clay bottom, the multiplication factors are 1.0 for the diameter, and 2.3 for both depth and lip height; hence, the required values are:

	(*a*) *Feet*	(*b*) *Feet*	
Diameter (factor 1.0)	1,000	1,900	
Depth (factor 2.3)	100	276	
Lip height (factor 2.3)	5.5	32	*Answer.*

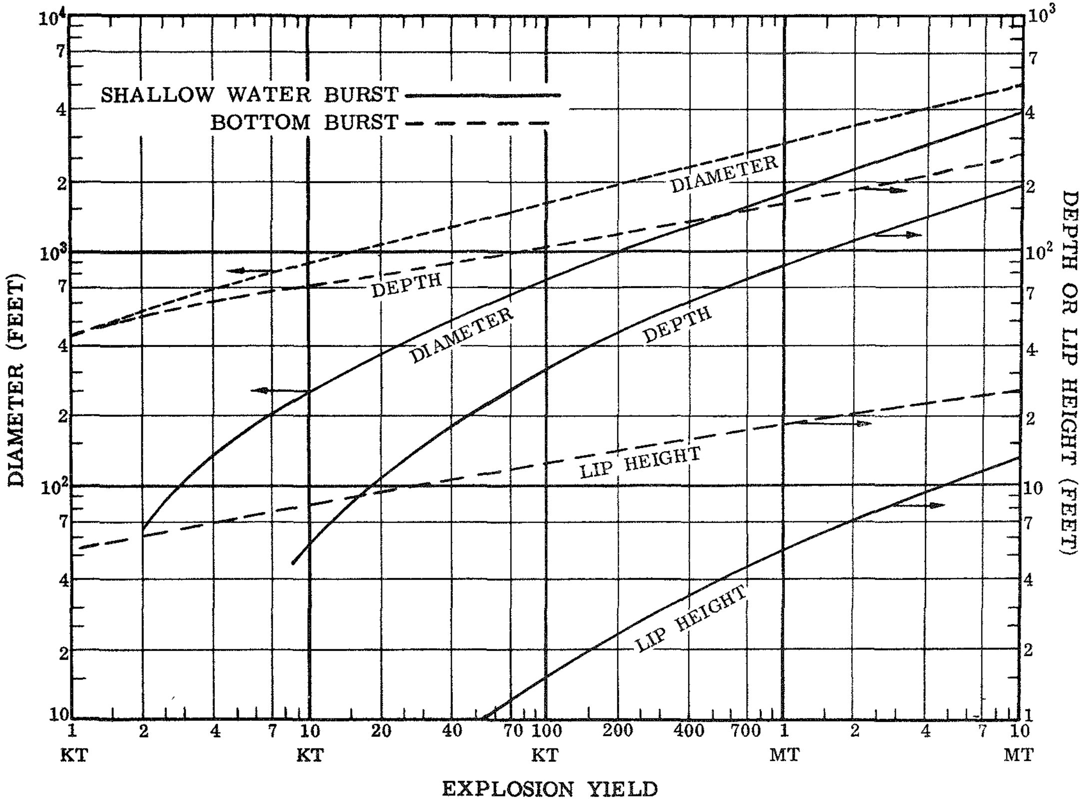

Figure 6.81. Dimensions of crater in underwater bursts as a function of explosion yield.

(Text continued from page 305.)

shock will be the important factor in determining damage. Exceptions to this rule may occur if the underwater burst is very near the surface or a weapon of very high yield is detonated in shallow water. In these cases, the air blast would be more significant than water shock.

6.83 The various types of damage to ships from underwater shock are defined in the same manner as for air blast. Thus, the general descriptions in Table 4.53 are applicable, irrespective of whether water shock or air blast is the main cause of damage. The energy-distance relationships for various degrees of damage to merchant-type ships due to air blast are given in Fig. 4.58b.

Damage to Hydraulic Structures

6.84 As is the case with air blast, it is to be expected that the damage to an underwater structure resulting from water shock will depend upon the dimensions of the structure and certain characteristic times. The particular times which appear to be significant are, on the one hand, the time constant of the shock wave (§ 6.75) and, on the other hand, the natural response (or plastic) time and the diffraction time of the structure, i.e., the time required for the diffracted pressure (shock) wave to be propagated distances of the order of magnitude of the dimensions of the structure. In the event that the underwater structure is near the surface, the cutoff time (§ 6.28) would be significant in certain cases.

6.85 If the time constant of the pressure wave and the cutoff time are large compared to the times which are characteristic of the structure, that is to say, if the water shock wave is one of relatively long duration, the effect of the shock is similar to that of an applied steady (or static) pressure. In these circumstances, the peak pressure is the appropriate criterion of damage. Such would be the case for small, rigid underwater structures, since they can be expected to have short characteristic times.

6.86 For large, rigid underwater structures, where the duration of the shock wave is short in comparison with the characteristic times of the structure, the impulse of the shock wave will be significant in determining the damage (Fig. 6.73). It should be remembered, in this connection, that the magnitude of the impulse and damage will be greatly decreased if the reflected wave from the air-

water surface reaches the target soon after the arrival of the primary shock wave.

6.87 If the large underwater structure can accept a substantial amount of permanent (plastic) deformation, as a result of impact with the shock front, it appears that the damage depends essentially on the energy of the shock wave (Fig. 6.73). If the structure is near the surface, the cutoff effect will decrease the amount of shock energy available for causing damage.

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*These documents may be obtained for a small charge from the Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C.

TABLE 7.40

APPROXIMATE RADIANT EXPOSURES FOR IGNITION OF FABRICS*

Material	Weight	Ignition exposure** (cal/sq cm)		
	oz/sq yd	*40 kilotons*	*1 megaton*	*10 megatons*
Rayon gabardine (black)	6	9	20	26
Rayon-acetate drapery (wine)	5	9	22	28
Rayon gabardine (gold)#	7	(***)	24	28
Rayon twill lining (black)	3	7	17	25
Rayon twill lining (beige)	3	13	20	28
Acetate-shantung (black)#	3	10	22	35
Cotton chenille bedspread (light blue)#	-----------	(***)	11	15
Cotton venetian blind tape, dirty (white)	-----------	10	18	22
Cotton muslin oiled window shade (green)	8	7	13	19
Cotton corduroy (brown)	8	11	16	22
Cotton canvas (O.D.)	12	12	18	28
Cotton denim, new (blue)	10	12	27	44
Cotton venetian blind strap (white)#	-----------	13	27	31
Cotton shirting (khaki)	3	14	21	28
Cotton heavy draperies (dark colors)	13	15	18	34

*Certain materials listed in previous editions and printings have been deleted.

**The values given are for near sea level detonations of weapons of the yields indicated. Ignition levels (except where marked #) are estimated to be valid within ± 25% under standard laboratory conditions. Under typical field conditions the values listed are estimated to be valid within ± 50% with a greater likelihood of higher rather than lower values. For materials marked #, ignition levels are estimated to be valid within ± 50% under laboratory conditions and within ± 100% under field conditions.

***Data not available or appropriate scaling not known.

7.42 Roughly speaking, something like 10 to 15 calories per square centimeter of thermal energy are required to produce visible charring of unpainted and unstained pine, douglas fir, redwood, and maple. Dark staining increases the tendency of the wood to char, but light-colored paints and hard varnishes provide protection.[2]

7.43 Glass is highly resistant to heat, but as it is very brittle it is sometimes replaced by transparent or translucent plastic materials or combined with layers of plastic, as in automobile windshields, to make it shatterproof. These plastics are organic compounds and so are subject to decomposition by heat. Nevertheless, many plastic materials, such as Bakelite, cellulose acetate, Lucite, Plexiglas, polyethylene, and Teflon, have been found to withstand thermal radiation remarkably well. At least 60 to 70 calories per square centimeter of thermal energy are required to produce surface melting or darkening.

[2] The thermal radiation energy incident on the front of the house referred to in § 7.33 was about 25 calories per square centimeter.

Radiant Exposures for Ignition of Various Materials

7.44 In connection with the initiation of fires, the radiant exposures required for the ignition of various common household and other materials are of great interest. Studies have been made both in the laboratory and at nuclear tests, and although the results are by no means definitive, they do provide a general indication of the amount of thermal energy per unit area that would be needed to cause a particular material to ignite. The data in Table 7.44 have been divided into two sections: one contains household materials and the other combustible substances which might start forest fires.

7.45 As far as the forest fuels are concerned, in particular, the radiant exposures required for ignition are greatly dependent upon the amount of moisture they contain. For the present purpose, it has been assumed that the leaves and grass are fairly dry, so that the radiant exposures given in Table 7.44 are essentially minimum values. In the presence of some dry fuel, thermal radiation may start a fire; it will then spread among combustible materials of higher moisture content which could not be directly ignited by the radiation.

Thermal Energy-Distance Relationships

7.46 In order to utilize the data in Tables 7.40 and 7.44 to determine how far from the burst point, for an explosion of given energy yield, ignition of a particular material would be observed, it is required to know how the thermal energy varies with distance. For a specific explosion yield, the variation of radiation exposure with distance from the point of burst depends upon a number of factors, including the height of burst and the condition (or clarity) of the atmosphere. As seen earlier, the proportion of the total yield that appears as thermal energy and the character and duration of the thermal pulse vary with the height of burst, especially if it is over about 100,000 feet (20 miles). Furthermore, the height of burst and the atmospheric visibility determine the fraction of the thermal energy that can penetrate the atmosphere without being absorbed.

7.47 The variation of radiant exposure with slant range from the explosion for a particular set of conditions can be conveniently

TABLE 7.44

APPROXIMATE RADIANT EXPOSURE FOR IGNITION OF HOUSEHOLD MATERIALS AND DRY FOREST FUELS*

Material	Weight	Ignition exposure** (cal/sq cm)		
	oz/sq yd	*40 kilotons*	*1 megaton*	*10 megatons*
Newspaper, shredded	2	4	6	11
Newspaper, dark picture area	2	5	7	12
Newspaper, printed text area	2	6	8	15
Paper, crepe (green)	1	6	9	16
Cotton string scrubbing mop, used (gray)#		10	15	21
Cotton string mop, weathered (cream)#		10	19	26
Matches, paper book, blue head exposed#		11	14	20
Excelsior, ponderosa pine (light yellow)#	2 lb/cu ft	(***)	23	23
Paper, Kraft, single sheet (tan)	3	10	13	20
Paper, bristol board, 3 ply (dark)	10	16	20	40
Paper, Kraft, carton, flat side, used (brown)	16	16	20	40
Paper, bond, typing, new (white)#	2	24	30	50
Dry rotted wood punk (fir)#		4	6	8
Deciduous leaves (beech)		4	6	8
Fine grass (cheat)		5	8	10
Coarse grass (sedge)		6	9	11
Pine needles, brown (ponderosa)		10	16	21

*Certain materials listed in previous editions and printings have been deleted.

**The values given are for near sea level detonations of weapons of the yields indicated. Ignition levels (except where marked #) are estimated to be valid within ±25% under standard laboratory conditions. Under typical field conditions the values listed are estimated to be valid within ±50% with a greater likelihood of higher rather than lower values. For materials marked #, ignition levels are estimated to be valid within ±50% under laboratory conditions and within ±100% under field conditions.

***Data not available or appropriate scaling not known.

represented in the form of Fig. 7.47. The curves in this figure apply to air bursts at moderate altitude, i.e., below about 20 miles, with the clarity of the atmosphere equivalent to a visibility of 50 miles, as defined in § 7.12. Suppose it is required to determine the range over which ignition may occur in newspaper as a result of exposure to a 1,000-kiloton (1-megaton) air burst under the given conditions. According to Table 7.44, the radiant exposure for ignition of the material in a 1-megaton explosion is about 8 calories per square centimeter. Entering Fig. 7.47 at the point on the vertical axis corresponding to 1 megaton, the horizontal line is followed until it intersects the curve for 8 calories per square centimeter of thermal radiation. The intersection is seen to correspond to a distance of about 9 miles from the explosion and this is the range over which

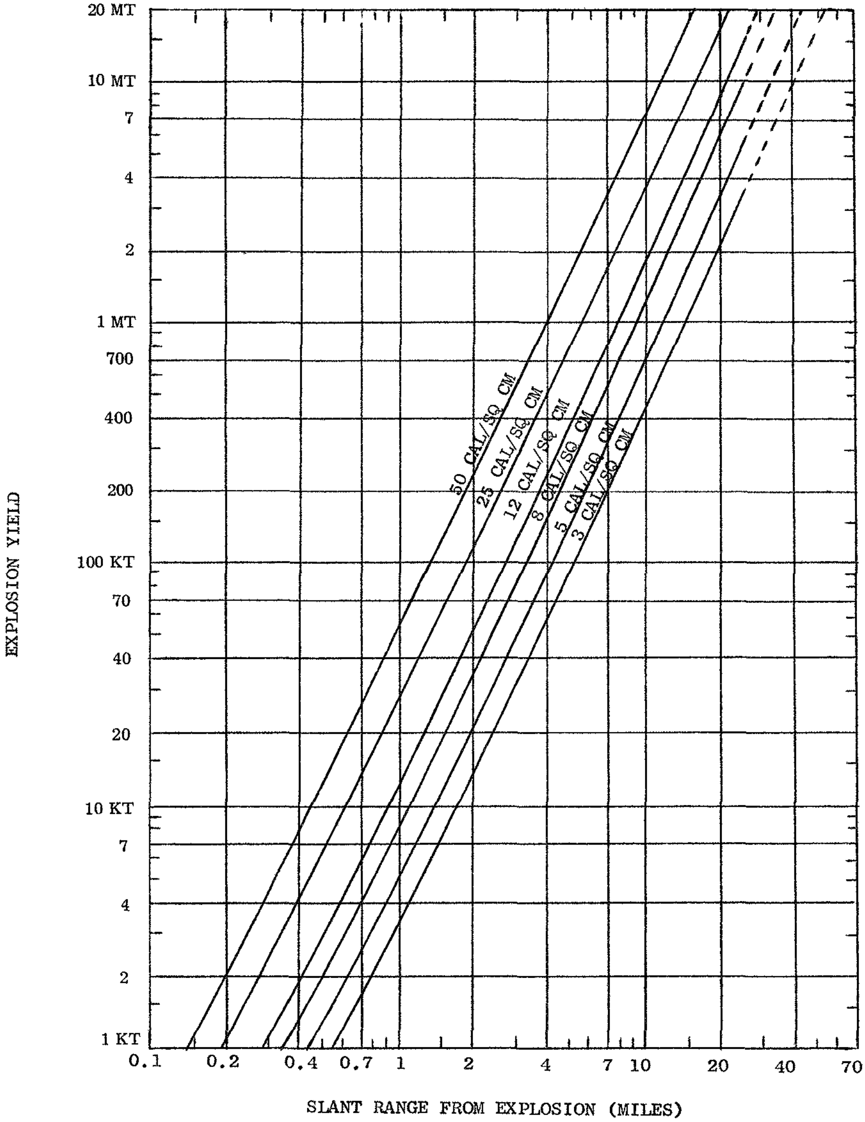

Figure 7.47. Slant ranges for specified radiant exposures as a function of energy yield of an explosion at moderate altitude (less than 20 miles) for 50-mile visibility.

ignitions may be started in newspaper as a direct result of the absorption of thermal radiation. Under hazy atmospheric conditions, or in the event of a surface burst, the distances obtained from Fig. 7.47 may be decreased. Similarly, in accordance with discussion in § 7.21 *et seq.*, a layer of dense cloud or smoke between the target and the point of burst will decrease the distance over which ignitions may occur.

Thermal Effects on Materials in Japan[3]

7.48 Apart from the actual ignition of combustible materials resulting in fires being started, which will be referred to later, a number of other phenomena observed in Japan testified to the intense heat due to the absorption of thermal radiation. Fabrics (Fig. 7.48a), utility poles (Fig. 7.48b), trees, and wooden posts, up to a radius of 11,000 feet (2.1 miles) from ground zero at Nagasaki, and 9,000 feet

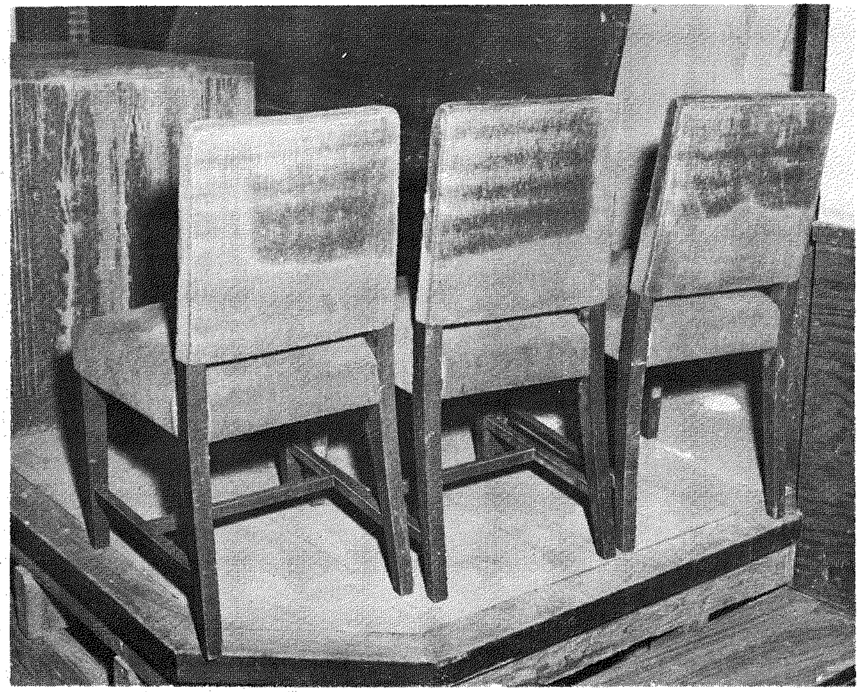

Figure 7.48a. Flash burns on upholstery of chairs exposed to bomb flash at window (1 mile from ground zero at Hiroshima).

[3] The effects of thermal radiations on human beings in Japan are described in Chapter XI.

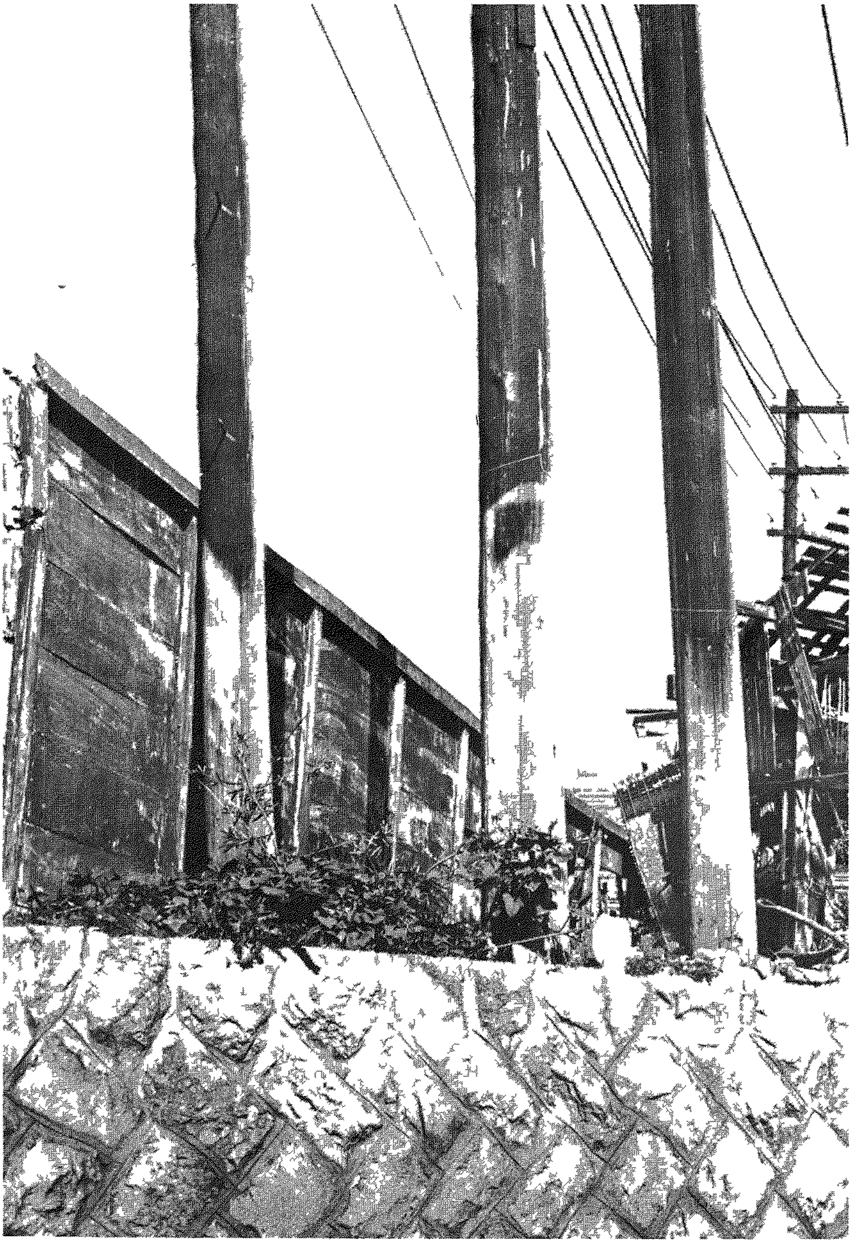

Figure 7.48b Flash burns on wooden poles (1.7 miles from ground zero at Nagasaki). The uncharred portions were protected from thermal radiation by a fence.

(1.7 miles) at Hiroshima (3 to 4 calories per square centimeter), if not destroyed in the general conflagration, were charred and blackened, but only on the side facing the point of burst. Where there was protection by buildings, walls, hills, and other objects there was no evidence of thermal radiation effects.

7.49 An interesting case of shadowing of this kind was recorded at Nagasaki. The tops and upper parts of a row of wooden posts were heavily charred, but the charred area was sharply limited by the shadow of a wall. The wall was, however, completely demolished

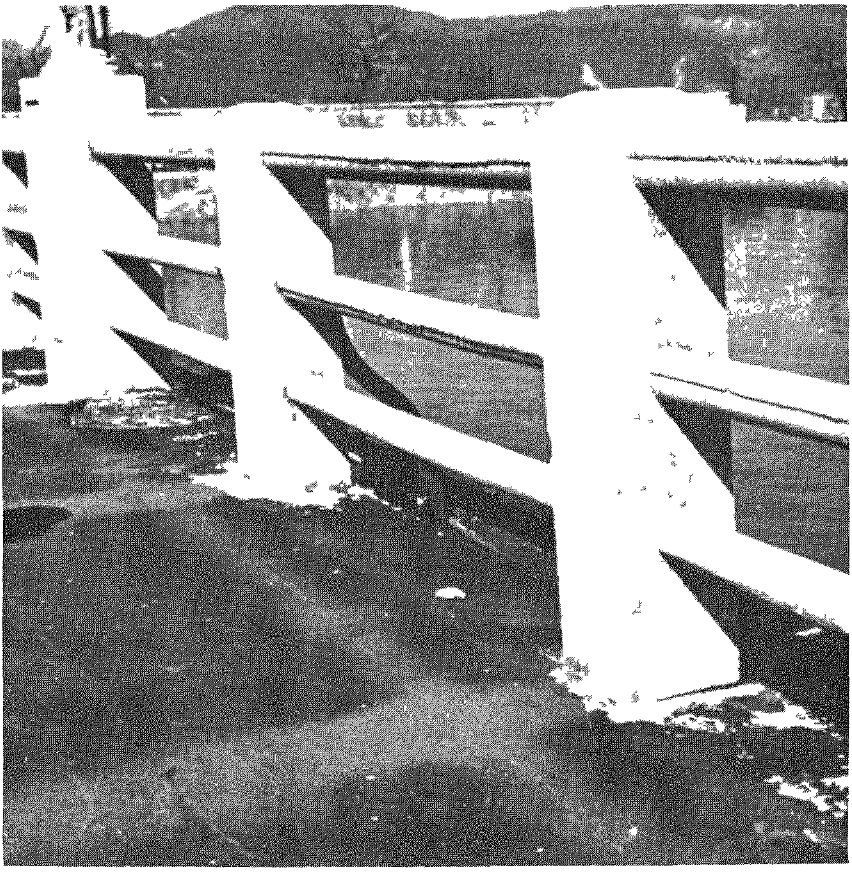

Figure 7.50a. Flash marks produced by thermal radiation on asphalt of bridge in Hiroshima. Where the railings served as a protection from the radiation, there were no marks; the length and direction of the "shadows" indicate the point of the bomb explosion.

by the blast wave which arrived after the thermal radiation. This radiation travels with the speed of light, whereas the blast wave advances much more slowly (§ 3.14).

7.50 From observations of the shadows left by intervening objects where they shielded otherwise exposed surfaces (Figs. 7.50 a and b), the direction of the center of the explosion was located with considerable accuracy. Furthermore, by examining the shadow effects at various places around the explosion, a good indication was obtained of the height of burst. Occasionally, a distinct penumbra was found,

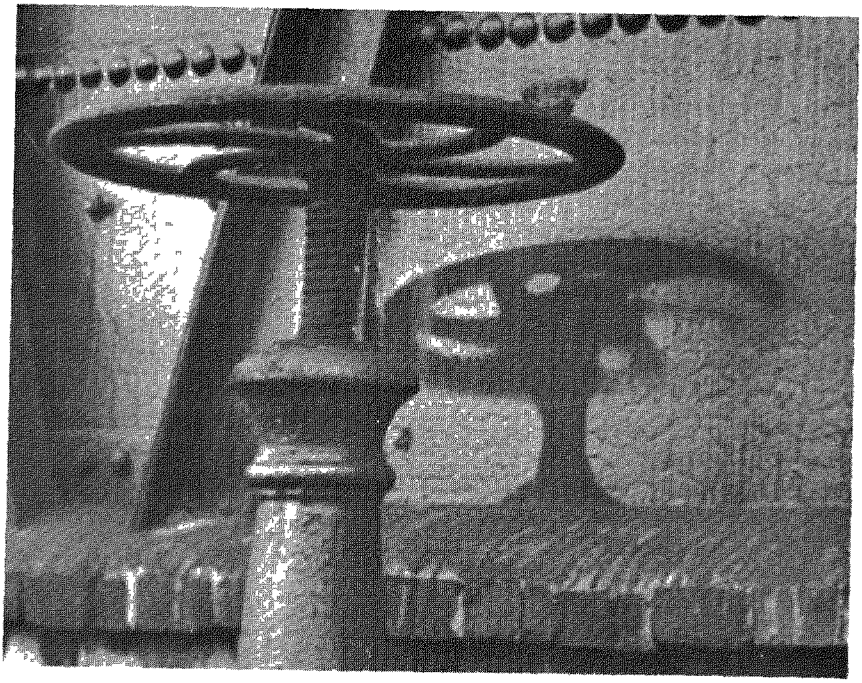

Figure 7.50b. Paint on gas holder scorched by the thermal radiation, except where protected by the valve (1.33 miles from ground zero at Hiroshima)

and from this it was possible to calculate the diameter of the fireball at the time the thermal radiation intensity was at a maximum.

7.51 One of the striking effects of the radiation was the roughening of the surface of polished granite where there was direct exposure. This roughening was attributed to the unequal expansion of the constituent crystals of the stone, and it is estimated that a temperature of at least 600° C (1,100° F) was necessary to produce the observed

results. From the depth of the roughening and ultimate flaking of the granite surface, the depth to which this temperature was attained could be determined. These observations were used to calculate the maximum ground temperatures at the time of the explosion. As mentioned in § 7.31, they were extremely high, especially near ground zero.

7.52 Another thermal effect, which proved to be valuable in subsequent studies, was the bubbling or blistering of the dark green (almost black) tile with a porous surface which is widely used for roofing in Japan (Fig. 7.52). The phenomenon was observed out to 3,900 feet (0.75 mile) from the explosion center, where the radiant exposure was about 40 calories per square centimeter. The size of the bubbles and their extent increased with proximity to ground zero, and also with the directness with which the tile itself faced the

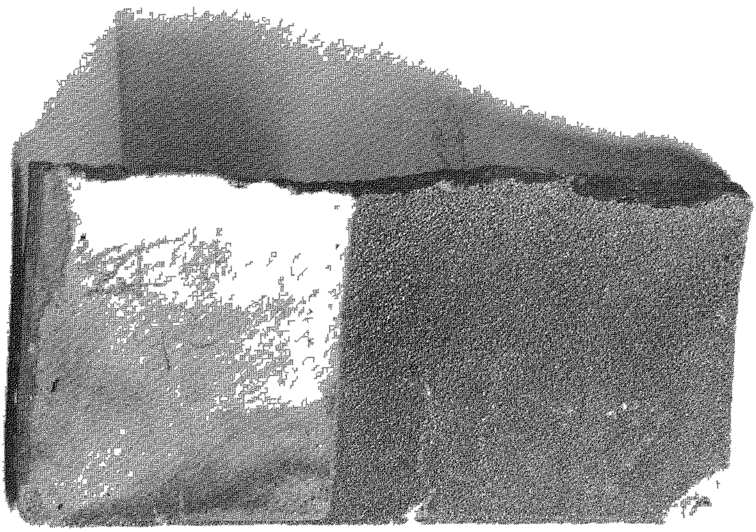

Figure 7.52. Blistered surface of roof tile; left portion of the tile was shielded by an overlapping one (0 37 mile from the explosion at Hiroshima)

explosion. In a laboratory test, using undamaged tile of the same kind, it was found that similar blistering could be obtained by heating to 1,800° C (3,270° F) for a period of 4 seconds, although the effect extended deeper into the tile than it did in Japan. From this result, it was concluded that in the nuclear explosion the tile attained a

temperature of more than 1,800° C (3,270° F) for a period of less than 4 seconds.

7.53 The difference in behavior of light and dark fabrics exposed to thermal radiation in Japan is also of considerable interest. Light-colored fabrics either reflect or transmit most of the thermal radiation and absorb very little. Consequently, they will not reach such a high temperature and will suffer less damage than dark fabrics which absorb a large proportion of the radiation. In one case, a shirt con-

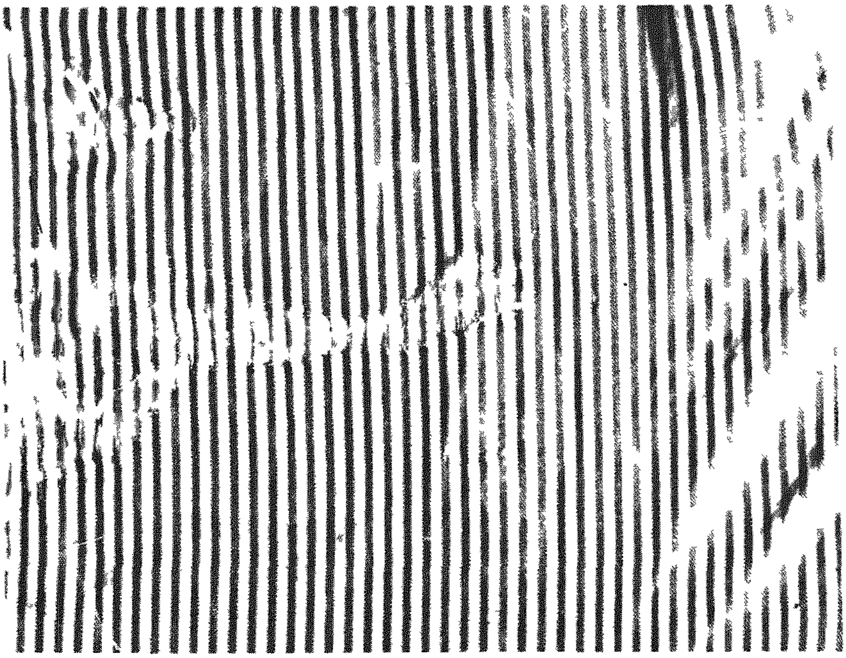

Figure 7.53. The light-colored portions of the material are intact, but some of the dark-colored stripes have been destroyed by the heat from the thermal radiation.

sisting of alternate narrow light and dark gray stripes had the dark stripes burned out, whereas the light-colored stripes were undamaged (Fig. 7.53). Similarly, a piece of paper, which had been exposed about 7,800 feet (1.5 miles) from ground zero (5 calories per square centimeter), had the characters, written in black ink, burned out, but the rest of the paper was not greatly affected.

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INCENDIARY EFFECTS

ORIGIN OF FIRES

7.54 There are two general ways in which fires can originate in a nuclear explosion. First, by the ignition of paper, trash, window curtains, awnings, excelsior, dry grass, and leaves, as a direct result of the absorption of thermal radiation. And second, as an indirect effect of the destruction caused by the blast wave, fires can be started by upset stoves and furnaces, electrical short-circuits, and broken gas lines. No matter how the fire originates, its subsequent spread will be determined by the amount and distribution of combustible materials in the vicinity. The manner whereby fires in cities grow and spread from ignition points is a complex matter which will be discussed later. In the meantime, two aspects of the problem of the development of fires accompanying a nuclear explosion will be considered, namely, (1) the number of points at which fires originate, and (2) the character of the surrounding area.

7.55 The initiation of secondary (or indirect) fires is difficult to analyze, but there are some aspects of direct ignition by thermal radiation which are reasonably clear. The most important appears to be what has been called the "density of ignition points." This is the number of points in a given area, e.g., an acre, where exterior combustible materials are present which will produce a primary ignition and may result in a fire. In general, these materials may be expected to ignite when exposed to at least the appropriate radiant energy values given in Tables 7.40 and 7.44. The data in Fig. 7.55 are based on surveys made in a number of large cities in the United States. It is seen that the density of ignition points is greatest in wholesale distribution and slum residential areas, and is least in good residential and large manufacturing areas.[4] Paper was the commonest ignitable material found everywhere except in downtown retail areas where awnings represented the major source of fire.

7.56 The density of ignition points provides some indication of the chance of fires being started under ideal weather conditions. But the results in Fig. 7.55 are by themselves not sufficient to permit an estimate to be made of the number of significant fires that will actually result. In the first place, at locations closer to ground zero where moderate to severe blast damage occurs, almost all ignitable materials will constitute a fire hazard. On the other hand, at greater distances, only those most easily ignitable will catch fire. Further,

[4] The area types are in accordance with the classification used by the U.S. Bureau of Census.

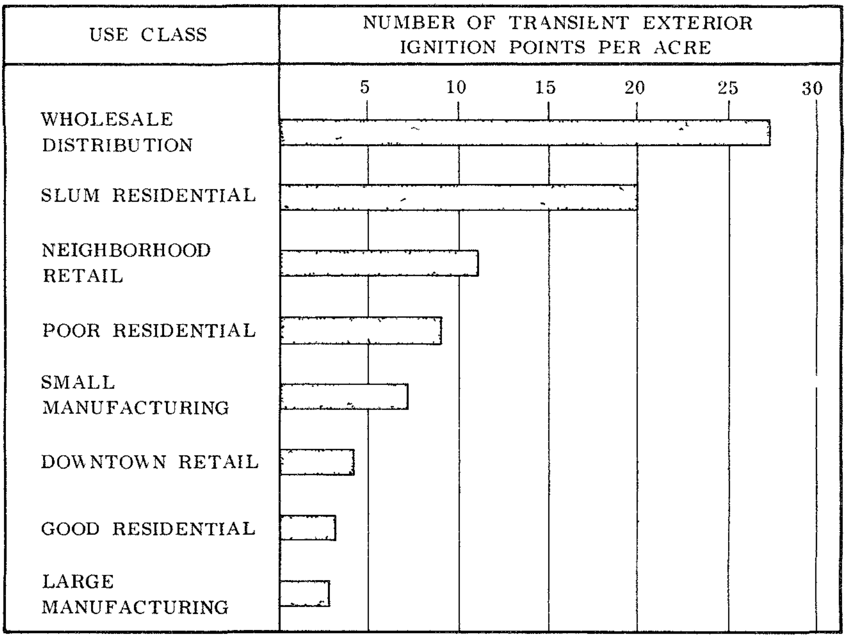

Figure 7.55 Frequency of exterior ignition points for various areas in a city

the formation of a significant fire, capable of spreading, will require appreciable quantities of combustible material close by, and this may not always be available.

7.57 The fact that accumulations of ignitable trash close to a wooden structure represent a real fire hazard was demonstrated at the nuclear tests carried out in Nevada in 1953. In these tests, three miniature wooden houses, each having a yard enclosed with a wooden fence, were exposed to 12 calories per square centimeter of thermal radiation. One house, at the left of Fig. 7.57, had weathered siding showing considerable decay, but the yard was free from trash. The next house also had a clean yard and in addition, the exterior siding was well maintained and painted. In the third house, at the right of the photograph, the siding, which was poorly maintained, was weathered, and the yard was littered with trash.

7.58 The state of the three houses after the explosion is seen in Fig. 7.58. The third house, at the right, soon burst into flame and was burned to the ground. The first house, on the left, did ignite but it did not burst into flame for 15 minutes. The well maintained house in the center with the clean yard suffered scorching only. It is of interest to recall that the wood of a newly erected white-painted

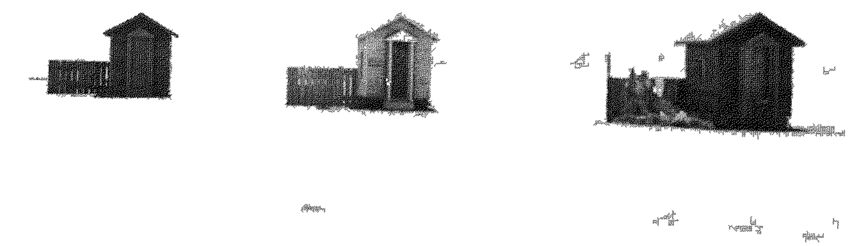

Figure 7.57 Wooden test houses before exposure to a nuclear explosion, Nevada Test Site

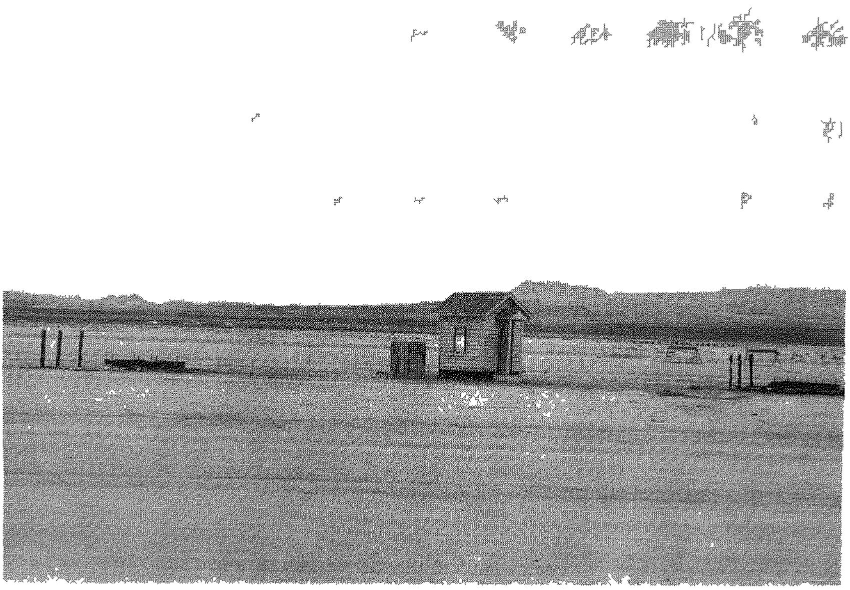

Figure 7.58 Wooden test houses after exposure to a nuclear explosion

house exposed to about 25 calories per square centimeter was badly charred but did not ignite (see Fig. 7.33b).

7.59 The value of fire-resistive furnishing in decreasing the number of ignition points was also demonstrated in the tests. Two identical, sturdily constructed houses, each having a window 4 feet by 6 feet facing the point of burst, were erected where the thermal radiation exposure was 17 calories per square centimeter. One of the houses contained rayon drapery, cotton rugs, and clothing, and, as was expected, it burst into flame immediately after the explosion and burned completely. In the other house, the draperies were of vinyl plastic, and rugs and clothing were made of wool. Although much ignition occurred, the recovery party, entering an hour after the explosion, was able to extinguish the fires.

7.60 There is another point in connection with the initiation of fires by thermal radiation that needs consideration. This is the possibility that the flame resulting from the ignition of a combustible material may be subsequently extinguished by the blast wind. It was thought that there was evidence for such an effect from an observation made in Japan (§ 7.67), but this may have been an exceptional case. The matter has been studied, both in connection with the effects in Japan and at various nuclear tests, and the general conclusion is that the blast wind has no significant effect in extinguishing fires (§ 7.68).

Spread of Fires

7.61 The spread of fires in a city, including the development of a "fire storm" to which reference is made in § 7.75, depends upon a variety of conditions, e.g., weather, terrain, and closeness and combustibility of the buildings. Information concerning the growth and spread of fires from a large number of ignition points, such as might follow a nuclear explosion, and their coalescence into large fires (or conflagrations) is limited to the experience of World War II incendiary raids and the two atomic bomb attacks. There is consequently some uncertainty concerning the validity of extrapolating from these limited experiences to the behavior to be expected in other cities. It appears, however, that if other circumstances are more-or-less the same, an important criterion of the probability of fire spread is the distance between buildings. It is evident, from general considerations, that the lower the building density or "built-upness" of an area, the less will be the probability that fire will spread from one structure to another. Furthermore, the larger the spaces between buildings the greater the chances that the fire can be extinguished.

7.62 The curve in Fig. 7.62 gives a rough idea of how the probability of fire spread, expressed as a percentage, depends upon the average distance between buildings in a city. The results will be dependent, to some extent, upon the types of structures involved, e.g., whether they are fire-resistive or not, as well as upon the damage caused by the blast wave. It should be noted that Fig. 7.62 applies to fire spread accompanying a nuclear explosion, when a large number of small fires are started directly by thermal radiation and indirectly in other ways.

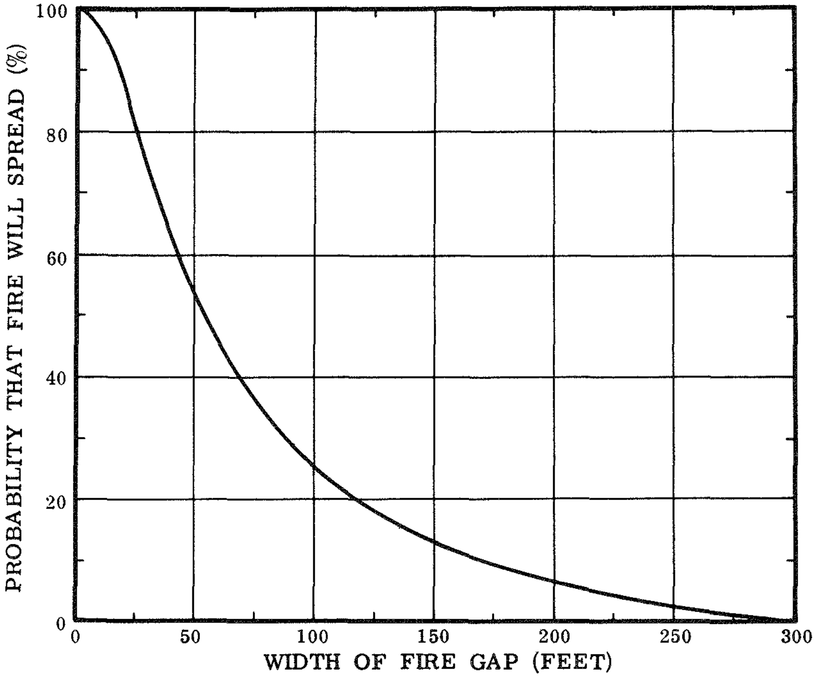

Figure 7.62. Width of gap and probability of fire spread.

7.63 Another aspect of fire spread is the development of mass fires in a forest following primary ignition of dried leaves, grass, and rotten wood by the thermal radiation. Some of the factors which will influence the growth of such fires are the moisture content of the trees, topography, and meteorological conditions. Low atmospheric humidity, strong winds, and steep terrain favor the development of forest fires. In general, a deciduous forest, particularly when in leaf, may be expected to burn less rapidly and with less intensity than a forest of coniferous trees. Green leaves and the trunks of trees would act as shields against thermal radiation, so that the number of points at which ignition occurs in a forest may well be less than would appear at first sight.

INCENDIARY EFFECTS IN JAPAN

The Nuclear Bomb as an Incendiary Weapon

7.64 The incendiary effects of a nuclear explosion do not present any especially characteristic features. In principle, the same overall result, as regards destruction by fire and blast, might be achieved by the use of conventional incendiary and high-explosive bombs. It has been estimated, for example, that the fire damage to buildings and other structures suffered at Hiroshima could have been produced by about 1,000 tons of incendiary bombs distributed over the city. It can be seen, however, that since this damage was caused by a single nuclear bomb of only 20 kilotons energy yield, nuclear weapons are capable of causing tremendous destruction by fire, as well as by blast.

7.65 Evidence was obtained from the nuclear explosions over Japan that the damage by fire is much more dependent upon local terrain and meteorological conditions than are blast effects. At both Hiroshima and Nagasaki the distances from ground zero at which particular types of blast damage were experienced were much the same. But the ranges of incendiary effects were quite different. In Hiroshima, for example, the total area severely damaged by fire, about 4.4 square miles, was roughly four times as great as in Nagasaki. One contributory cause was the irregular layout of Nagasaki as compared with Hiroshima; also greater destruction could probably have been achieved by a change in the point of burst. Nevertheless, an important factor was the difference in terrain, with its associated building density. Hiroshima was relatively flat and highly built up, whereas Nagasaki had hilly portions near ground zero that were bare of structures.

Origin and Spread of Fires in Japan

7.66 Definite evidence was obtained from Japanese observers that the thermal radiation caused thin, dark cotton cloth, such as the black-out curtains that were in common use during the war, thin paper, and dry, rotted wood to catch fire at distance up to 3,500 feet (0.66 mile) from ground zero (about 35 calories per square centimeter). It was reported that a cedar bark roof farther out was seen to burst into flame, apparently spontaneously, but this was not definitely confirmed. Abnormal enhanced amounts of radiation, due to re-

Figure 7 66 The top of a wood pole was reported as being ignited by the thermal radiation (1 25 miles from ground zero at Hiroshima) Note the unburned surroundings, the nearest burned building was 360 feet away

flection, scattering, and focusing effects, might have caused fires to originate at isolated points (Fig. 7.66).

7.67 Interesting evidence of the ignition of sound wood was found about a mile from ground zero at Nagasaki, where the radiant exposure was approximately 15 calories per square centimeter. A light piece of wood, similar to the flat side of an orange crate, had its front surface charred. In addition, however, blackening was observed through cracks and nail holes, where the thermal radiation would not have penetrated, and also around the edges adjoining the charred surface. A possible explanation is that the exposed surface of the wood had actually ignited, due to the heat from the thermal radiation, and the flames had spread through the cracks and holes around the edges for several seconds, before they were extinguished by the blast wind.

7.68 From the evidence of charred wood found at both Hiroshima and Nagasaki, it was originally concluded that such wood had actually been ignited by thermal radiation and that the flames were subsequently extinguished by the blast. But it now seems more probable that, apart from some exceptional instances, such as that just described, there was no actual ignition of the wood. The absorption of the thermal radiation caused charring in sound wood but the temperatures were generally not high enough for ignition to occur (§ 7.33). Rotted and checked wood and excelsior, however, have been observed to burn completely, and the flame was not greatly affected by the blast wave.

7.69 It is not known to what extent thermal radiation contributed to the initiation of fires in the nuclear bombings in Japan. It is possible that, up to a mile or so from ground zero, some fires may have originated from secondary causes, such as upsetting of stoves, electrical short-circuits, broken gas lines, and so on, which were a direct effect of the blast wave. A number of fires in industrial plants were initiated by furnaces and boilers being overturned, and by the collapse of buildings on them.

7.70 Once the fires had started, there were several factors, directly related to the destruction caused by the nuclear explosion, that influenced their spreading. By breaking windows and blowing in or damaging fire shutters (Fig. 7.70), by stripping wall and roof sheathing, and collapsing walls and roofs, the blast made many buildings more vulnerable to fire. Noncombustible (fire-resistive) structures were often left in a condition favorable to the internal spread of fires by damage at stairways, elevators, and in firewall openings as well as by the rupture and collapse of floors and partitions (see Fig. 5.89d).

7.71 On the other hand, when combustible frame buildings were blown down, they did not burn as rapidly as they would have done had they remained standing. Moreover, the noncombustible debris produced by the blast frequently covered and prevented the burning of combustible material. There is some doubt, therefore, whether on the whole the effect of the blast was to facilitate or to hinder the development of fires at Hiroshima and Nagasaki.

Figure 7.70. Fire shutters in building blown in or damaged by the blast; shutter at center probably blown outward by blast passing through building (0.57 mile from ground zero at Hiroshima).

7.72 Although there were firebreaks, both natural, e.g., rivers and open spaces, and artificial, e.g., roads and cleared areas, in the Japanese cities, they were not very effective in preventing the fires from spreading. The reason was that fires often started simultaneously on both sides of the firebreaks, so that they could not serve their intended purpose. In addition, combustible materials were frequently strewn across the firebreaks and open spaces, such as yards and street areas, by the blast, so that they could not prevent the spread of fires. Nevertheless, there were a few instances where firebreaks assisted in preventing the burnout of some fire-resistive buildings.

7.73 One of the important aspects of the nuclear attacks on Japan was that, in the large area that suffered simultaneous blast damage, the fire departments were completely overwhelmed. It is true that the fire-fighting services and equipment were poor by American standards, but it is doubtful if much could have been achieved, under the circumstances, by more efficient fire departments. At Hiroshima, for example, 70 percent of the fire-fighting equipment was crushed in the collapse of fire houses, and 80 percent of the personnel were unable to respond. Even if men and machines had survived the blast, many fires would have been inaccessible because of the streets being blocked with debris. For this reason, and also because of the fear of being trapped, a fire company from an area which had escaped destruction was unable to approach closer than 6,600 feet (1.25 miles) from ground zero at Nagasaki. It was almost inevitable, therefore, that all buildings within this range would be destroyed.

7.74 Another contributory factor to the destruction by fire was the failure of the water supply in both Hiroshima and Nagasaki. The pumping stations were not largely affected, but serious damage was sustained by distribution pipes and mains, with a resulting leakage and drop in available water pressure. Most of the lines above ground were broken by collapsing buildings and by heat from the fires which melted the pipes. Some buried water mains were fractured and others were broken due to the collapse or distortion of bridges upon which they were supported (§ 5.117).

Fire Storm in Hiroshima

7.75 About 20 minutes after the detonation of the nuclear bomb at Hiroshima, there developed the phenomenon known as "fire storm." This consisted of a wind which blew toward the burning area of the city from all directions, reaching a maximum velocity of 30 to 40 miles per hour about 2 to 3 hours after the explosion, decreasing to light or moderate and variable in direction about 6 hours after. The wind was accompanied by intermittent rain, light over the center of the city and heavier about 3,500 to 5,000 feet (0.67 to 0.95 mile) to the north and west. Rain is often associated with a fire storm and is apparently due to the condensation of moisture on particles from the fire when they reach a cooler area. Because of the strong inward draft at ground level, the fire storm was a decisive factor in limiting the spread of fire beyond the initial ignited area. It accounts for the fact that the radius of the burned-out area was so uniform in Hiroshima and was not much greater than the range in which fires started soon after the explosion. However, virtually everything combustible within this region was destroyed.

7.76 It should be noted that the fire storm is by no means a special characteristic of nuclear weapons. Similar fire storms have been reported as accompanying large forest fires in the United States, and especially after incendiary bomb attacks in both Germany and Japan during World War II. The high winds are produced largely by the updraft of the heated air over an extensive burning area. They are thus the equivalent, on a very large scale, of the draft of a chimney under which a fire is burning. Because of limited experience, the conditions for the development of fire storms in cities are not well known. It appears, however, that some, although not necessarily all, of the essential requirements are the following: (1) thousands of nearly simultaneous ignitions over an area of at least a square mile, (2) heavy building density, e.g., more than 20 percent of the area is covered by buildings, and (3) little or no ground wind. Based on these criteria, only certain sections—usually the older and slum areas—of a very few cities in the United States would be susceptible to fire storm development.

7.77 It should be mentioned that no definite fire storm occurred at Nagasaki, although the velocity of the southwest wind, blowing between the hills, increased to 35 miles an hour when the conflagration had become well established, perhaps about 2 hours after the explosion. This wind tended to carry the fire up the valley in a direction where there was nothing to burn. Some 7 hours later, the wind had shifted to the east and its velocity had dropped to 10 to 15 miles per hour. These winds undoubtedly restricted the spread of fire in the respective directions from which they were blowing. The small number of dwellings exposed in the long narrow valley running through Nagasaki probably did not furnish sufficient fuel for the development of a fire storm as compared to the many buildings on the flat terrain at Hiroshima.

TECHNICAL ASPECTS OF THERMAL RADIATION[5]

Distribution and Absorption of Energy From the Fireball

7.78 Spectroscopic studies made in the course of weapons tests have shown that the fireball does not behave exactly like a black body, i.e., as a perfect radiator. Generally, the proportion of radiations of longer wave length (greater than 5,500 A)[6] corresponds to higher black body temperatures than does the shorter wave emission. The assumption of black body behavior for the fireball, however, serves as a reasonable approximation in interpreting the thermal

[5] The remaining sections of this chapter may be omitted without loss of continuity.

[6] The symbol "A" represents the "angstrom", i.e., 10^{-8} cm, the unit in which radiation wave lengths are commonly expressed.

radiation emission characteristics. For a black body, the distribution of radiant energy over the spectrum can be related to the surface temperature by Planck's radiation equation. If $E_\lambda d\lambda$ denotes the energy density, i.e., energy per unit volume, in the wave length interval λ to $\lambda+d\lambda$, then,

$$E_\lambda=\frac{8\pi hc}{\lambda^5}\cdot\frac{1}{e^{hc/\lambda kT}-1}, \tag{7.78.1}$$

where c is the velocity of light, h is Planck's quantum of action, k is Boltzmann's constant, i.e., the gas constant per molecule, and T is the absolute temperature. It will be noted that hc/λ is the energy of the photon of wave length λ (§ 1.70).

7.79 From the Planck equation it is possible to calculate the rate of energy emission (or radiant power) of a black body for a given wave length, i.e., J_λ, as a function of wave length for any specified temperature, since

$$J_\lambda=\frac{c}{4}E_\lambda, \tag{7.79.1}$$

where J_λ is in units of energy (ergs) per unit area (cm^2) per unit time (sec) per unit wave length (A). The results of such calculations for temperatures ranging from 100 million (10^8) degrees to 2,000° K are shown in Fig. 7.79. It is seen that the total radiant power, which is given by the area under each curve, decreases greatly as the temperature is decreased.

7.80 An important aspect of Fig. 7.79 is the change in location of the curves with temperature; in other words, the spectrum of the radiant energy varies with the temperature. At high temperatures, radiations of short wave length predominate, but at low temperatures those of long wave length make the major contribution. For example, in the exploding weapon, before the formation of the fireball, the temperature is several tens of million degrees Kelvin. Most of the (primary) thermal radiation is then in the wave length range from about 0.1 to 100 A, i.e., 120 to 0.12 kev energy, corresponding roughly to the soft X-ray region. This is the basis of the statement made earlier that the primary thermal radiation from a nuclear explosion consists largely of X-rays. These radiations are absorbed by the surrounding air to form the fireball from which the effective thermal radiation of present interest is emitted. Since the surface temperature of the fireball is generally below 10,000° K, the radiation is mainly in the ultraviolet, visible, and infrared regions of the spectrum. The dimensions of the fireball in which the thermal X-rays are absorbed depends on the ambient air density, as will be seen shortly.

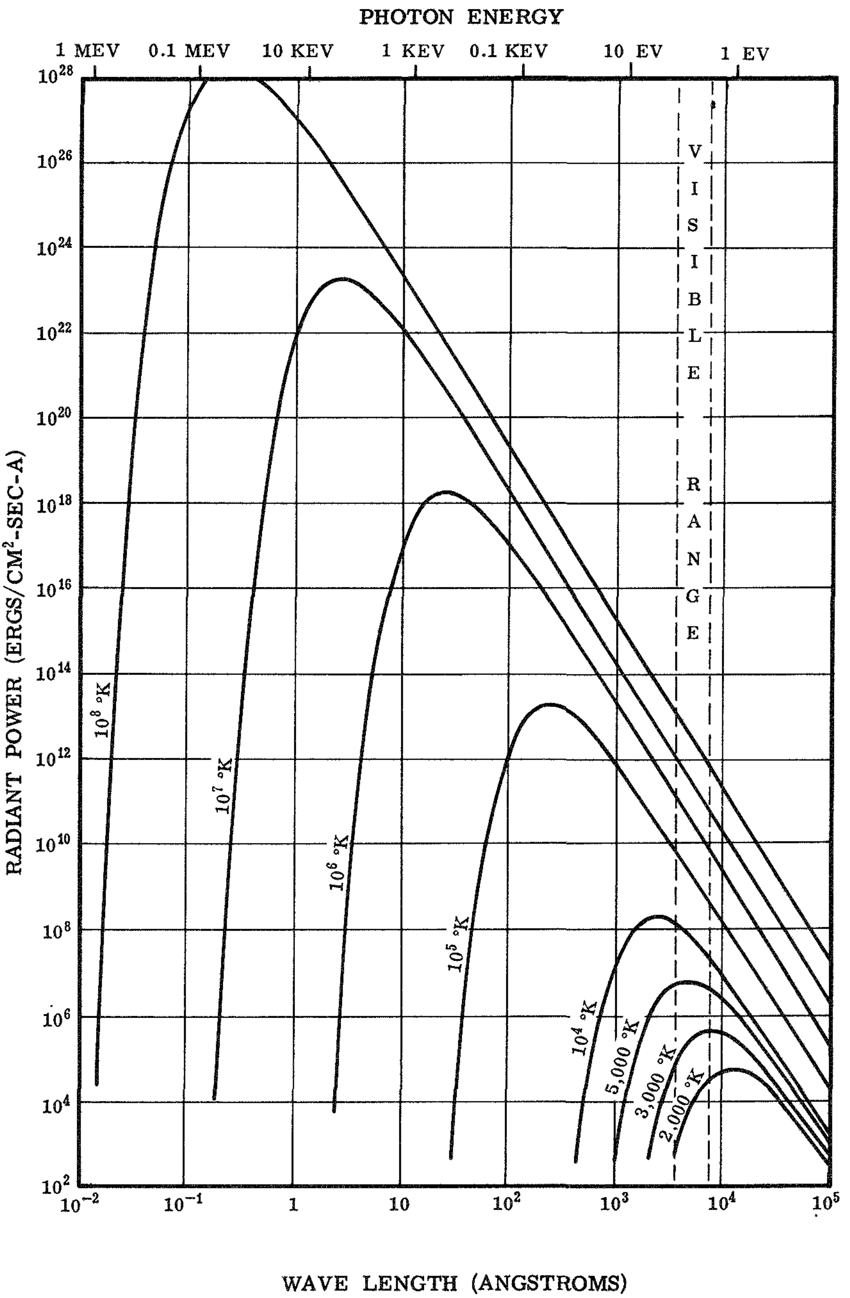

Figure 7.79. Radiant power of a black body as a function of wave length at various temperatures.

7.81 It will be recalled that the thermal radiation received at the earth's surface differs to some extent from that leaving the fireball. The reason is that the radiations of shorter wave length, i.e., in the ultraviolet, are more readily absorbed than the others by the atmosphere between the burst point and the earth's surface. The thermal radiation received at a distance from a nuclear explosion is fairly characteristic of a black body at a temperature of about 6,000 to 7,000° K, although somewhat depleted in the ultraviolet and other shorter wave lengths. Even if the detonation occurs at very high altitudes, the thermal radiation from the low-density fireball must pass through the denser atmosphere before reaching the ground. The effective thermal radiation received on the earth's surface is thus also composed of the longer wave lengths.

7.82 An expression for the wave length (λ_m) corresponding to the maximum in the radiant power as a function of the black body temperature can be obtained by differentiating equation (7.79.1) with respect to wave length and equating the result to zero. It is then found that

$$\lambda_m = \frac{C}{T}, \tag{7.82.1}$$

where C is a constant, equal to 2.90×10^7 angstroms-degrees K. This expression is known as Wien's displacement law.

7.83 The temperature at which the maximum in the radiant power distribution from a black body should just fall into the visible spectrum, i.e., wave length 3,850 A, is found from equation (7.82.1) to be about 7,500° K. This happens to be very close to the maximum surface temperature of the fireball after the minimum, i.e., during the second radiation pulse (Fig. 2.113). Since the apparent surface temperature generally does not exceed 8,000° K and the average is considerably less, it is evident that most of the thermal energy emitted in the second pulse should consist mainly of visible and infrared rays, with little in the ultraviolet region of the spectrum. This has been found to be the case in actual tests, even though the fireball deviates appreciably from black body behavior at this stage.

7.84 The mean free path (§ 2.104) in cold air, at sea-level density, of X-ray photons with energies from about 0.5 to 15 kev is given by the approximate relationship

$$\text{Mean free path} \approx \frac{E^3}{5} \text{ cm}, \tag{7.84.1}$$

where E is the photon energy in kilo-electron volts (kev). In order to make some order-of-magnitude calculations of the distances in

which thermal X-rays from a nuclear explosion are absorbed in air, a convenient round-number temperature of 10^7 degrees Kelvin will be used for simplicity. According to equation (7.82.1), the wave length at which the rate of emission of radiation from a black body at this temperature is a maximum is 2.9 A. According to equation (1.70.2) this corresponds to a photon energy of 4.3 kev, and from equation (7.84.1) the mean free path of these photons in normal air is about 15 cm. In traversing a distance of one mean free path the energy of the radiations decreased by a factor of e, i.e., approximately 2.7; hence 90 percent of the energy will be deposited within a radius of 2.3 mean free paths. It is seen, therefore, that 4.3-kev radiation will be largely absorbed in a distance of about 35 cm, i.e., a little over 1 foot, in a sea-level atmosphere.

7.85 The primary thermal radiations from a nuclear explosion cover a wide range of wave lengths, as is evident from Fig. 7.79. However, for the present purpose, which is to obtain a rough indication of the initial size of the fireball, the wave length (or energy) at which the radiant power from a black body is a maximum may be taken as typical. It follows, therefore, from the results given above that the thermal X-rays from a nuclear explosion will be almost completely absorbed by about a foot of air at normal density. Because the oxygen and nitrogen in the air in the vicinity of the explosion are considerably ionized, they do not absorb as effectively as do neutral molecules. Nevertheless, in a nuclear explosion in the atmosphere where the air density does not differ greatly from the sea-level value, most of the X-rays, which constitute the primary thermal radiation, will be absorbed within a few feet of the explosion. It is in this manner that the initial fireball is formed in an air burst.

7.86 With increasing altitude, the air density decreases roughly by a factor of ten for every 10 miles (see § 10.75), so that at 150,000 feet (approximately 30 miles) the density is about 10^{-3} of the sea-level value. The mean free path of the photon varies inversely as the density, so that for nuclear explosions at an altitude of about 30 miles, the region of the air heated by X-rays, which is equivalent to the fireball, extends over a radius of some thousands of feet. In spite of the lower density, the mass of heated air in this large volume is much greater than in the fireball associated with a nuclear explosion at lower altitudes, and so the temperature attained by the air is lower.

7.87 At altitudes of about 100,000 to 350,000 feet (20 to 70 miles) the manner in which the thermal radiation is emitted from a nuclear detonation is somewhat different from that at lower altitudes. At

the upper limit (350,000 feet), the heated (fireball) region can be about 0.5 to 6 miles in extent for yields of 1 kiloton to 1 megaton, respectively. The time required for a shock wave to form is of the order of 0.1 to 1 sec for these yields. For the reasons given in § 2.123, the thermal radiation is emitted from the fireball in a single pulse of relatively short duration. The limited data available indicate that the thermal radiation received on the ground from bursts at high altitudes is consistent with the statement (§ 7.25) that roughly 25 to 35 percent of the total yield of the weapon is converted into effective thermal radiation.

7.88 For altitudes in excess of 350,000 feet (above 70 miles) the air density is less than 10^{-7} of that at sea level. The mean free path of the dominant thermal X-rays produced in a nuclear explosion is then several hundred miles. In spite of the low density, the mass of air in which the thermal energy is deposited is many million tons, and so the temperature will not increase appreciably. At the low air temperatures, the thermal radiation emitted from an explosion in the megaton range is incapable of causing damage at the earth's surface.

Total Radiant Power From Fireball

7.89 According to the Stefan-Boltzmann law, the total amount of energy (of all wave lengths), J, radiated per square centimeter per second by a black body in all directions in one hemisphere is related to the absolute temperature, T, by the equation

$$J=\sigma T^4, \tag{7.89.1}$$

where σ is the Stefan-Boltzmann constant. The value of J can also be obtained by integration of equation (7.79.1) over all wave lengths from zero to infinity. It is then found that

$$\begin{aligned}\sigma&=2\pi^5k^4/15h^3c^2\\&=5.67\times10^{-5}\text{ erg/(cm}^2\text{) (sec) (deg}^4\text{)}\\&=1.38\times10^{-12}\text{ cal/(cm}^2\text{) (sec) (deg}^4\text{).}\end{aligned}$$

With σ known, the total radiant energy intensity from the fireball behaving as a black body can be readily calculated for any required temperature.

7.90 In accordance with the definition of J, given above, it follows that the total rate of emission of radiant energy from the fireball can be obtained upon multiplying the expression in equation

(7.89.1) by the area. If R is the radius of the fireball, its area is $4\pi R^2$, so that the total rate of thermal energy emission (or total radiant power) is $\sigma T^4 \times 4\pi R^2$. Representing this quantity by the symbol P, it follows that

$$P = 4\pi\sigma T^4 R^2$$

$$= 1.71 \times 10^{-11}\ T^4 R^2 \text{ calories per second,}$$

where T is in degrees Kelvin and R is in centimeters. Alternatively, if the radius, R, is expressed in feet, then,

$$P = 1.59 \times 10^{-8}\ T^4 R^2 \text{ calories per second.} \qquad (7.90.1)$$

7.91 The powei, P, is measured directly as a function of time, t, for each explosion, but instead of plotting P versus t, a curve is drawn of the scaled power, i.e., P/P_{max}, versus the scaled time, i.e., t/t_{max}, where P_{max} is the maximum value of the thermal power, corresponding to the temperature maximum in the second pulse, and t_{max} is the time at which this maximum is attained. The resulting (left scale) curve, shown in Fig. 7.91 is then of general applicability, irrespective of the yield of the explosion. The zero of the scaled time axis is taken as the time of the first minimum; as seen in §2.116, this is approximately equal to $0.0025 W^{1/2}$ second, where W is the total explosion yield in kilotons. The first pulse is so short that the amount of thermal radiation energy received prior to the first minimum is only about 1 percent of the total.

7.92 In order to make the power-time curve specific for any particular explosion energy yield, it is necessary to know the appropriate values of P_{max} and t_{max}. These are related approximately to the yield, W kilotons, in the following manner for air bursts:

$$P_{max} \approx 4 W^{1/2} \text{ kilotons per second,}$$

and

$$t_{max} \approx 0.032\ W^{1/2} \text{ seconds.}$$

For air bursts in the megaton range, the value of t_{max} may be somewhat less than given by this expression. For a contact surface burst the fireball develops in a manner approaching that for an air burst of twice the yield, because the blast wave energy is reflected back from the surface into the fireball (§§ 2.117, 3.30). Hence, t_{max} may be expected to be larger than for an air burst of the same actual yield.

7.93 The amount of thermal energy, E, emitted by the fireball in an air burst up to any specified time can be obtained from the area

under the curve of P versus t up to that time. The result, expressed in percent as E/E_{tot} versus t/t_{max}, is shown by the second curve (right scale) in Fig. 7.91. The quantity E_{tot} is the total thermal energy emitted in the second pulse by the fireball; this may range from 30 to 40 percent of the energy yield of the explosion, but for the present purpose it will be assumed, for the reason given in § 7.04, that

$$E_{tot} \text{ (kilotons)} \approx {}^1/_3 W. \qquad (7.93.1)$$

This equation gives the thermal energy in terms of kilotons of TNT equivalent, but if it is required in calories the result is multiplied by 10^{12}.

7.94 The curves in Fig. 7.91 present some features of special interest. As is to be expected, the thermal power (or rate of emission of radiant energy) of the fireball rises to a maximum, just as does the temperature in the second radiation pulse. However, since the thermal power is roughly proportional to T^4, it increases and decreases much more rapidly than does the temperature. This accounts for the sharp rise to the maximum in the P/P_{max} curve, followed by a somewhat less sharp drop which tapers off as the fireball approaches its final stages.

7.95 From the standpoint of protection against skin burns (and possibly eye injury) by taking evasive action, the important quantity is t_{max}, since the rate of emission of thermal radiation from the fireball is then a maximum. It is seen from the relationship in § 7.92 that this time increases in proportion to the square root of the energy yield of the explosion. Thus, t_{max} is about 0.1 second for a 10-kiloton explosion, but it is some 3 seconds for a weapon with 10 megatons energy yield. At such respective distances where severe burns might be experienced, evasive action would thus be expected to achieve greater relative success for air bursts of high energy yield. The dependence of t_{max} on the explosion yield is indicated in another way in Fig. 7.95 which shows the percentage of the total thermal energy emitted at various times after the first minimum for 10- and 100-kiloton and 1- and 10-megaton air bursts. Close to 20 percent of the thermal energy will have been emitted at t_{max} in each case. At $10t_{max}$, which is taken as the effective duration of the second thermal pulse (§ 7.03), over 80 percent of the thermal radiation has been released.

7.96 The results described above are applicable to detonations at altitudes below about 100,000 feet (20 miles) where the density of the air is still appreciable. With increasing altitude, the fireball phenomena change, as described in Chapter II, and above 100,000 feet essentially all of the thermal energy is emitted in a single pulse of short

The curves in Fig. 7.91 show the variation with the scaled time, t/t_{max}, of the scaled fireball power, P/P_{max} (left ordinate) and of the percent of the total thermal energy emitted, E/E_{tot} (right ordinate), in the second thermal pulse of an air burst.

Scaling. In order to apply the data in Fig. 7.91 to an explosion of any energy, W kilotons, the following expressions are used:

$$P_{max} \approx 4W^{1/2} \text{ kilotons per second}$$

$$t_{max} \approx 0.032W^{1/2} \text{ seconds}$$

$$E_{tot} \approx \tfrac{1}{3}W \text{ kilotons,}$$

where t_{max} is the time after explosion for temperature maximum in second thermal pulse, P_{max} is the maximum rate (at t_{max}) of emission of thermal energy from fireball, and E_{tot} is the total thermal energy emitted by fireball in the second pulse.

Example

Given: A 500 KT burst.

Find: (*a*) The rate of emission of thermal energy, (*b*) the amount of thermal energy emitted, at 2 seconds after the explosion.

Solution: Since W is 500 KT, the value of $W^{1/2}$ is 22.4, so that $t_{max}=0.032\times22.4=0.72$ second, and the scaled time at 2 seconds after the explosion is

$$t/t_{max}=2.0/0.72=2.8.$$

(*a*) From Fig. 7.91, the value of P/P_{max} at this scaled time is 0.26, and since $P_{max}=4\times22.4=90$ kilotons per second, it follows that,

$$P=0.26\times90=23 \text{ kilotons per second}$$

$$=23\times10^{12} \text{ calories per second.} \quad \textit{Answer.}$$

(*b*) At the scaled time of 2.8, the value of E/E_{tot} from Fig. 7.91 is 58 percent, i.e., 0.58, and

$$E_{tot}=\tfrac{1}{3}\times500=167 \text{ kilotons.}$$

Hence,

$$E=0.58\times167=97 \text{ kilotons}$$

$$=97\times10^{12} \text{ calories.} \quad \textit{Answer.}$$

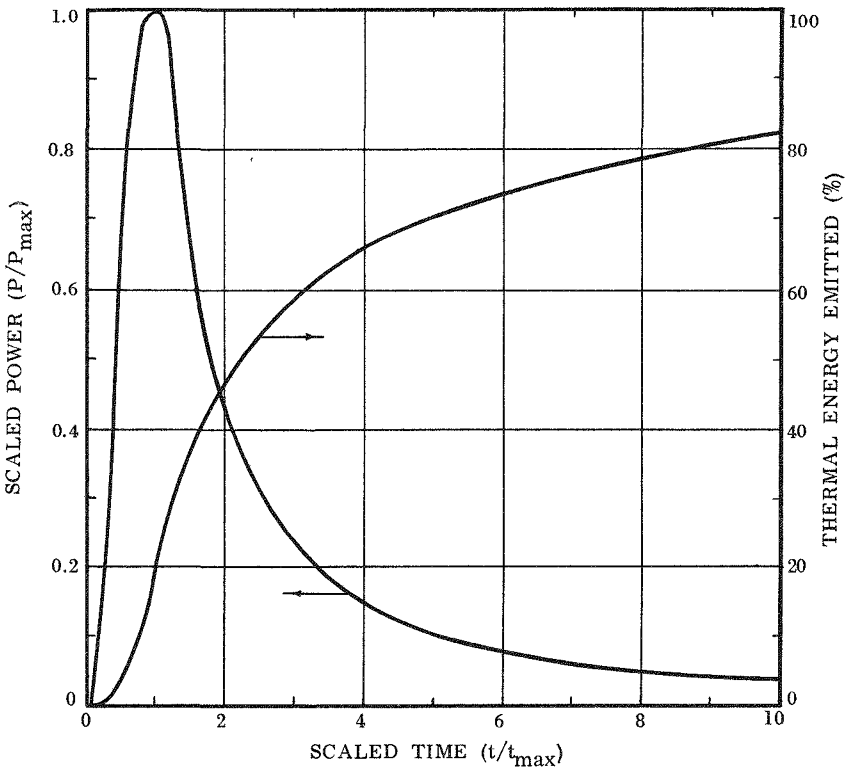

Figure 7.91. Scaled fireball power and fraction of thermal energy versus scaled time in second thermal pulse of an air burst.

duration, e.g., in less than a second for a megaton-range explosion at 250,000 feet altitude (§ 2.121). Scaling of the pulse length with respect to the explosion yield is very complex and depends upon a variety of factors. However, the duration of the pulse will probably not be strongly dependent on the total yield. At higher altitudes, the thermal pulse length may be expected to be longer because of the larger mass and lower temperature of the radiating fireball.

7.97 It appears that under such conditions that sufficient thermal radiation is received on the ground to cause skin burns, the emission time is too short to permit evasive action. For detonations in the megaton range occurring near the lower limit of the high-altitude region, i.e., around 20 miles, skin burns are possible on the earth's surface. But at higher altitudes, the distance of the explosion makes the probability very small that exposed persons on the ground will suffer such burns. On the other hand, altitude can increase the

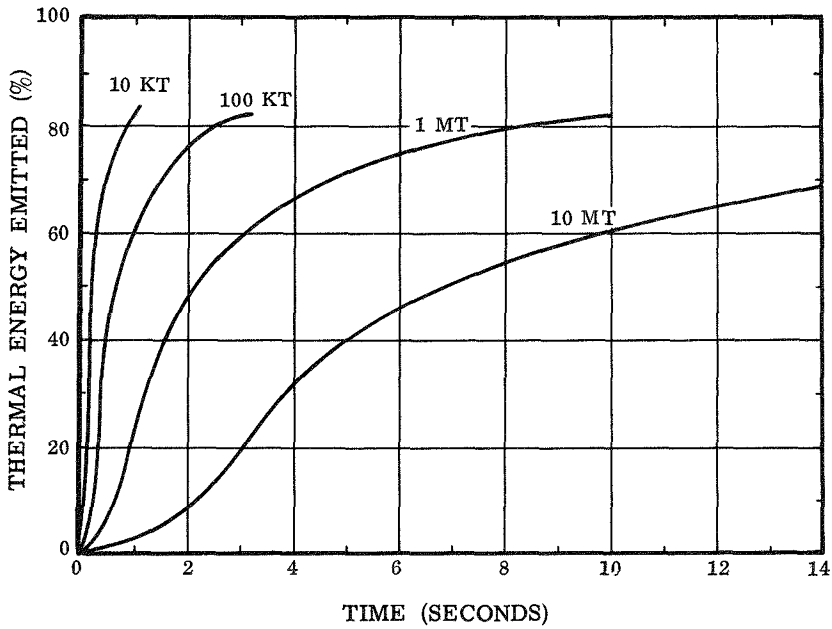

Figure 7.95. Percentage of thermal energy emitted as a function of time for air bursts of various yields.

possibility of eye injuries, especially of flash blindness (§7.37). During the period of the blink reflex (0.15 second), a significant portion of the thermal radiation from a high-altitude detonation will have been received on the ground. Furthermore, the light from the fireball will be visible over a considerable area. In fact, it is possible that a high-altitude nuclear explosion in the megaton range could produce effects on the eye at all distances up to the line of sight permitted by the earth's curvature.

Thermal Energy-Distance Relationship

7.98 The next matter to consider is the variation with distance from the explosion of the total thermal energy (in calories) received per square centimeter, i.e., thermal (or radiant) exposure, of a target material. As seen earlier in this chapter, such information, combined with the data in Fig. 7.46 (see also Fig. 7.105) and in Tables 7.40 and 7.44, permits estimates to be made of the probable ranges for various thermal radiation effects.

7.99 If there is no atmospheric attenuation, the thermal energy, E_{tot}, at a distance D from the explosion, may be regarded as being spread uniformly over the surface of a sphere of area $4\pi D^2$. The energy received per unit area of the sphere would thus be $E_{tot}/4\pi D^2$. If attenuation were due only to absorption in a uniform atmosphere, e.g., for an air burst, this quantity would be multiplied by the factor $e^{-\kappa D}$, where κ is an absorption coefficient averaged over the whole spectrum of wave lengths. Hence, in these circumstances, using the symbol Q to represent the radiant exposure, i.e., the energy received per unit area normal to the direction of propagation, at a distance D from the explosion, it follows that

$$Q=\frac{E_{tot}}{4\pi D^2}e^{-\kappa D}. \tag{7.99.1}$$

7.100 When scattering of the radiation occurs, in addition to absorption, the coefficient κ is no longer a constant but is a function of distance, and it is then not convenient to express the attenuation by means of an exponential factor. A more useful formulation which has been developed is represented by

$$Q=\frac{E_{tot}T}{4\pi D^2}, \tag{7.100.1}$$

where the transmittance, T, i.e., the fraction of the radiation (direct and scattered) which is transmitted, is a complex function of the visibility (scattering), absorption, and distance.[7]

7.101 The amount of thermal radiation energy, E_{tot}, emitted from a nuclear detonation can be related to the weapon yield W by the general expression

$$E_{tot}=fW, \tag{7.101.1}$$

where f is the fraction of the total yield in the form of thermal radiation energy. Hence, the radiant exposure can be expressed as

$$Q=\frac{fTW}{4\pi D^2} \tag{7.101.2}$$

by substituting fW for E_{tot} in equation (7.100.1).

[7] Scattered radiation does not cause permanent damage to the retina of the eye. Hence, to determine the effective radiant exposure in this connection equation (7.99.1) should be used; κ is about 0.03 km^{-1} for a visibility of 80 km (50 miles), 0.1 km^{-1} for 40 km (25 miles), and 0.2 km^{-1} for 20 km (12.4 miles). Scattered radiation can, however, contribute to flash blindness, resulting from the dazzling effect of bright light.

7.102 In a weapons test, it is possible to measure Q and W, and since the distance D from the explosion is known the magnitude of the product fT can be determined from equation (7.101.2). To obtain f, the value of T for the atmosphere between the explosion and the observation point must be known. However, the atmospheric transmittance over a long distance varies with both time and direction, so that the value at the instant when Q is measured cannot be obtained with a precision better than about ± 20 percent. Consequently, average values of T, such as those given in Fig. 7.104 below, are employed. Using these data and analyzing values of the product fT from a large number of weapons tests, f is found to range from about 0.3 to 0.4, with a mean of about one-third, for air bursts.

7.103 By utilizing the fact that 1 kiloton of TNT is equivalent to 10^{12} calories and taking f as $\frac{1}{3}$, equation (7.101.2) for an air burst becomes

$$Q(\text{cal/sq cm}) = \frac{10^{12}WT}{12\pi D^2}, \qquad (7.103.1)$$

where D is in centimeters. If the distance (or slant range) is expressed in miles, equation (7.103.1) reduces approximately to

$$Q(\text{cal/sq cm}) \approx \frac{1.04WT}{D^2}, \qquad (7.103.2)$$

where D is now in miles.

7.104 The value of T, for any given atmospheric condition, depends on the solid angle over which scattered radiation can reach a particular exposed object. For the present purpose it will be assumed that the target is such, e.g., an appreciable flat area, that scattered radiation is received from all directions above, in addition to the direct thermal radiation from the source. The variation of the transmittance with distance from the explosion for the two different visibility ranges is shown in Fig. 7.104; one curve is for a visibility of 50 miles and 5 grams of water vapor per cubic meter of air and the other is for a visibility of 10 miles and 10 grams of water vapor per cubic meter. The data may be considered to be reliable up to distances of half the visibility in each case.

7.105 In order to simplify the use of equation (7.103.2), in conjunction with Fig. 7.104, the values of the thermal radiation exposure, Q, in calories per square centimeter, for various distances (slant ranges), D, from an air burst are plotted for $W=1$ kiloton in Fig. 7.105. The results are applicable provided D is less than half the appropriate visibility, between 10 and 50 miles. The thermal energy

received from an explosion of W kilotons is then obtained upon multiplying the radiant exposure for the same distance in Fig. 7.105 by W. If the distances of interest are greater than half the visibility range, the thermal radiation exposures derived from Fig. 7.105 will be less reliable but in the majority of cases they will be conservative.

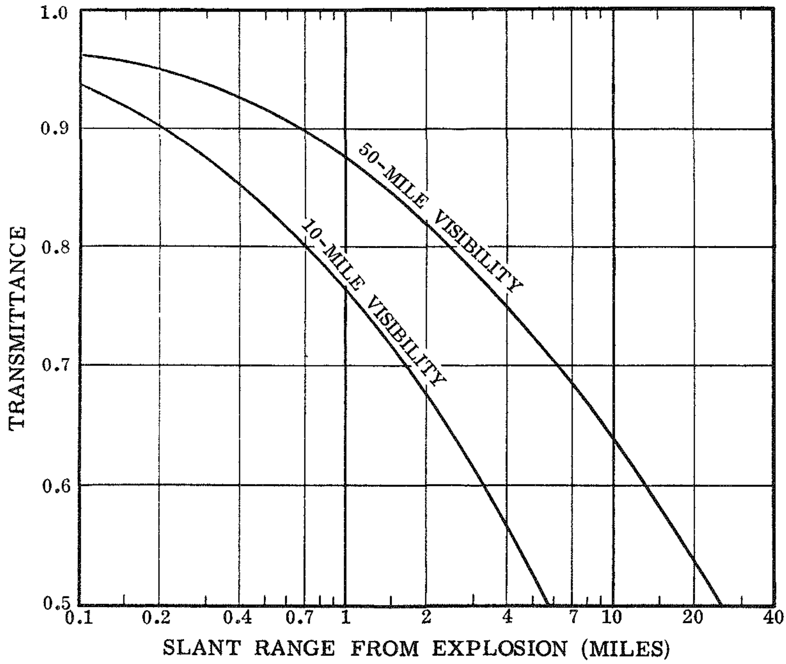

Figure 7.104. Atmospheric transmittance as a function of distance for visibilities of 10 miles and 50 miles.

7.106 For a surface burst, the radiant exposures along the earth's surface will be less than for equal distances from an air burst of the same total yield. This difference is partly due, as indicated in § 7.23, to the decreased transmittance of the intervening low air layer due to dust and water vapor produced by the explosion. Furthermore, the normal atmosphere close to the earth's surface transmits less than at higher altitudes. The thermal exposure from a surface burst thus ranges from about three-quarters at short distances to one-half at longer distances of the corresponding value for an air burst derived from equation (7.103.2) or from Fig. 7.105. In other words the f

The plot in Fig. 7.105, which is in two parts for convenience of representation, shows the amount of thermal energy (or radiant exposure) in calories per square centimeter received at various distances from a 1 KT air burst for atmospheric visibility between 10 and 50 miles.

Scaling. The radiant exposure at any specified distance from a W KT explosion is W times the value for the same distance from a 1 KT burst.

Example

Given: A 100 KT air burst and a visibility of between 10 and 50 miles.

Find: The radiant exposure received at a distance of 3 miles from the explosion.

Solution: From Fig. 7.104 the amount of thermal energy received at 3 miles from a 1 KT air burst is between 0.07 and 0.10 calorie per square centimeter. Consequently, the radiant exposure received at 3 miles from a 100 KT air burst is between

$$100 \times 0.07 = 7 \text{ calories per square centimeter.}$$

and

$$100 \times 0.10 = 10 \text{ calories per square centimeter.} \quad \textit{Answer.}$$

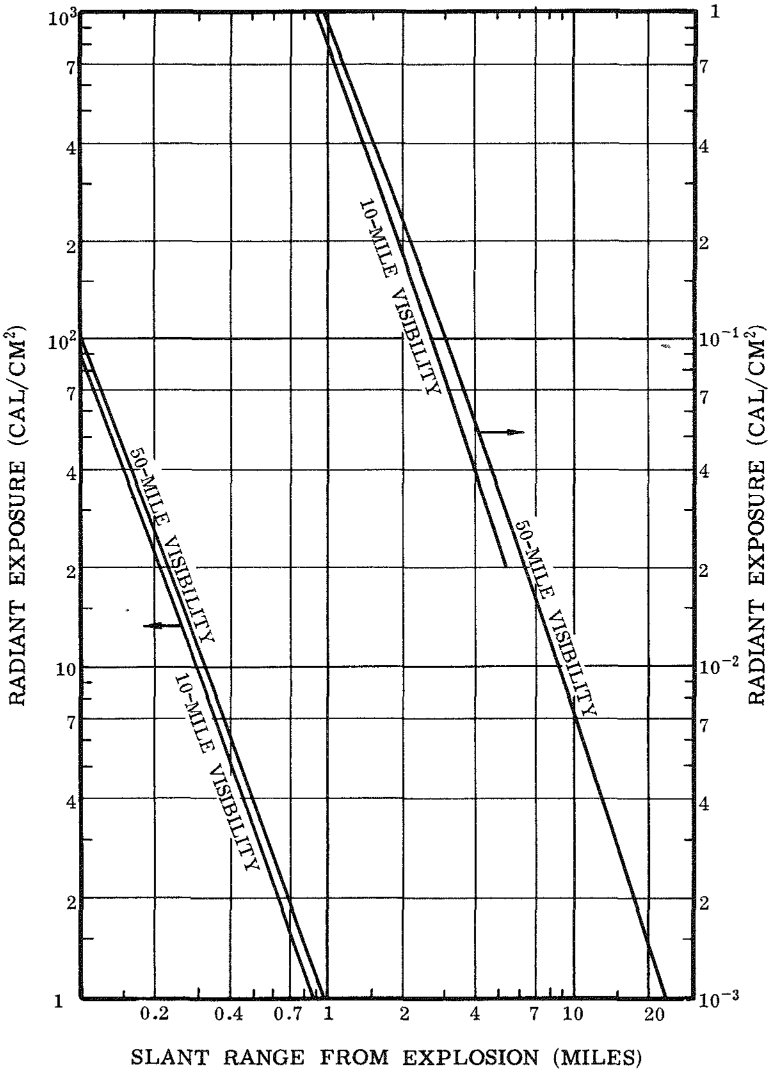

Figure 7.105. Radiant exposure as a function of slant range from a 1-kiloton air burst for visibilities of 10 miles and 50 miles.

factor of equation (7.101.2) has values which lie approximately between ¼ and ⅐. Thus, for a surface burst,

$$Q(\text{cal/sq cm}) \approx 0.8 \text{ to } 0.5 \frac{WT}{D^2}, \tag{7.106.1}$$

where D is the slant range in miles. It appears that as the yield increases the radiant exposure tends towards the larger limit of the values given by equation (7.106.1).

7.107 In the calculation of the thermal radiation exposure at some distance from a high-altitude nuclear explosion, e.g., at the earth's surface, equation (7.101.2), must be modified in two respects. First, the thermal energy capable of causing damage is approximately 25 to 35 percent of the total yield (§7.25), for detonations of altitudes from about 100,000 to 350,000 feet (20 to 70 miles). Correction for this difference can be made by taking E_{tot} to be roughly 0.25 W kilotons.

7.108 Second, in their passage from the burst point to the earth, the radiations pass through regions where the atmospheric density varies continuously and is considerably less than at sea level. The attenuation can be calculated in an approximate manner by utilizing the concept of the "reduced height of the atmosphere." This is equal to the total mass of air contained in a vertical column of unit cross section above the observer divided by the sea-level density of air. On the ground at sea level, the reduced height of the atmosphere is about 25,000 feet or roughly 5 miles. If an explosion occurs at an altitude of H miles, for example, it is assumed, for purposes of estimating the thermal attenuation, that, in arriving at a target on the ground vertically below the burst point, the radiation traverses $H-5$ miles of vacuum, in which there is no absorption or scattering, and 5 miles of sea-level atmosphere. If the explosion center is not immediately above the target, but makes an angle of elevation ϕ with the horizon, then the respective distances are $(H-5)/\sin\phi$ and $5/\sin\phi$, respectively.

7.109 On the basis of the foregoing argument, it can be shown that for a high-altitude explosion equation (7.103.2) can be written in the approximate general form

$$Q(\text{cal/sq cm}) \approx \frac{0.76\,WT}{H^2} \sin^2\phi \tag{7.109.1}$$

where T is the appropriate transmittance for the angle ϕ. If the shot is directly overhead, ϕ is 90° and $\sin^2\phi$ is unity. Values for the transmittance as a function of angle of elevation, for detonations at high altitude, are given in Fig. 7.109; with these data equation

(7.109.1) can be used to give results which are reliable within a factor of two or so. Observations of radiant exposure made on Johnston Island in connection with the TEAK shot, described in Chapter II, are in general agreement with equation (7.109.1).

7.110 For detonations at altitudes above about 70 miles, equation (7.109.1) is no longer applicable. As explained in §7.88, the volume of air heated by the thermal X-rays is so large that the temperatures attained are relatively low. Thermal radiation is then emitted at such a slow rate that, at distances of interest, the radiant energy capable of causing any kind of damage is less than for bursts of the same yield at lower altitudes.

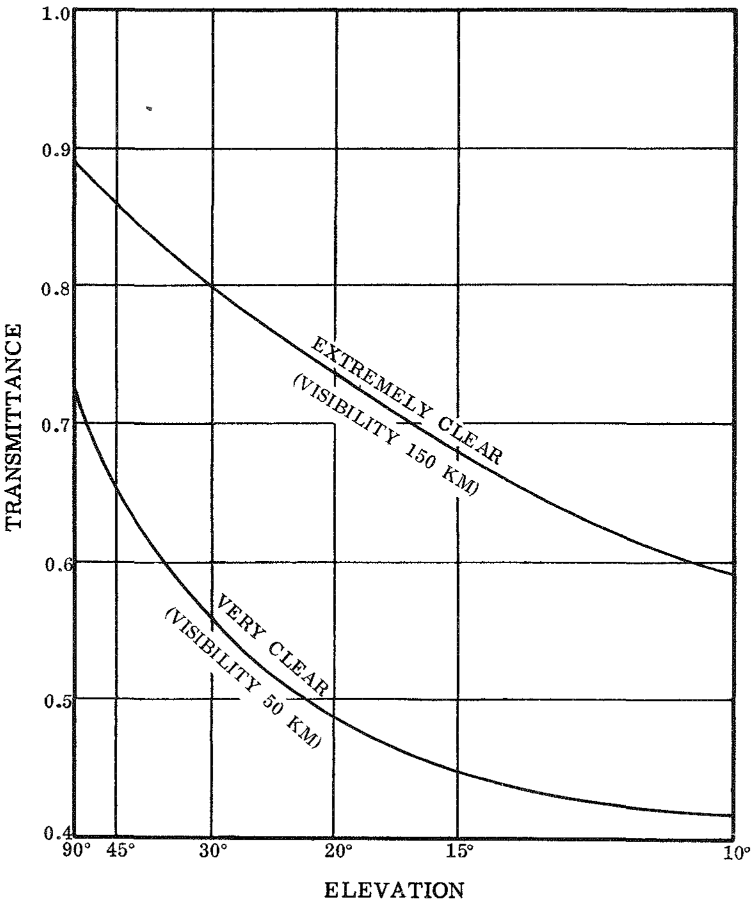

Figure 7.109. Atmospheric transmittance as a function of elevation for use in calculating radiant exposures from high-altitude explosions.

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*These documents may be obtained for a small charge from the Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C.

**These documents may be obtained from the Library of Congress, Washington 25, D.C.

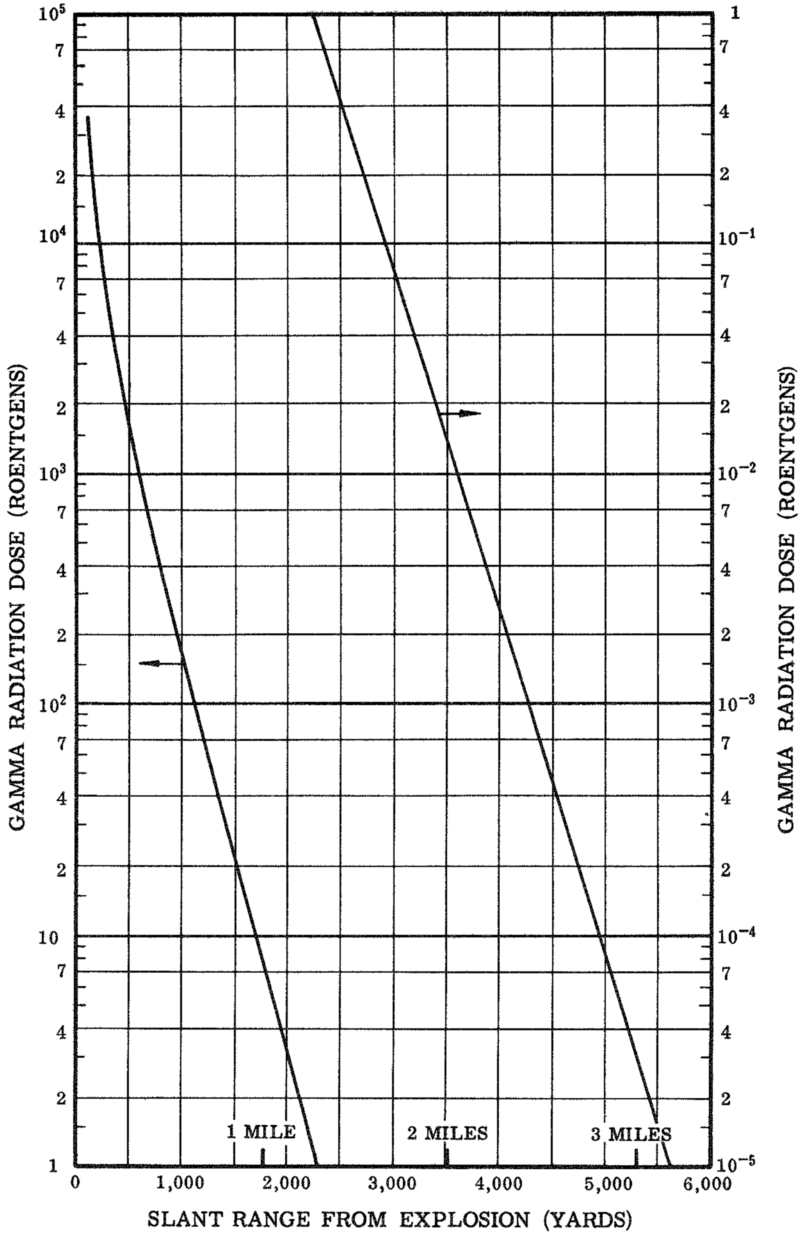

Figure 8.27a. Initial gamma-radiation dose as function of slant range from explosion for 1-kiloton air burst, based on 0.9 sea-level air density.

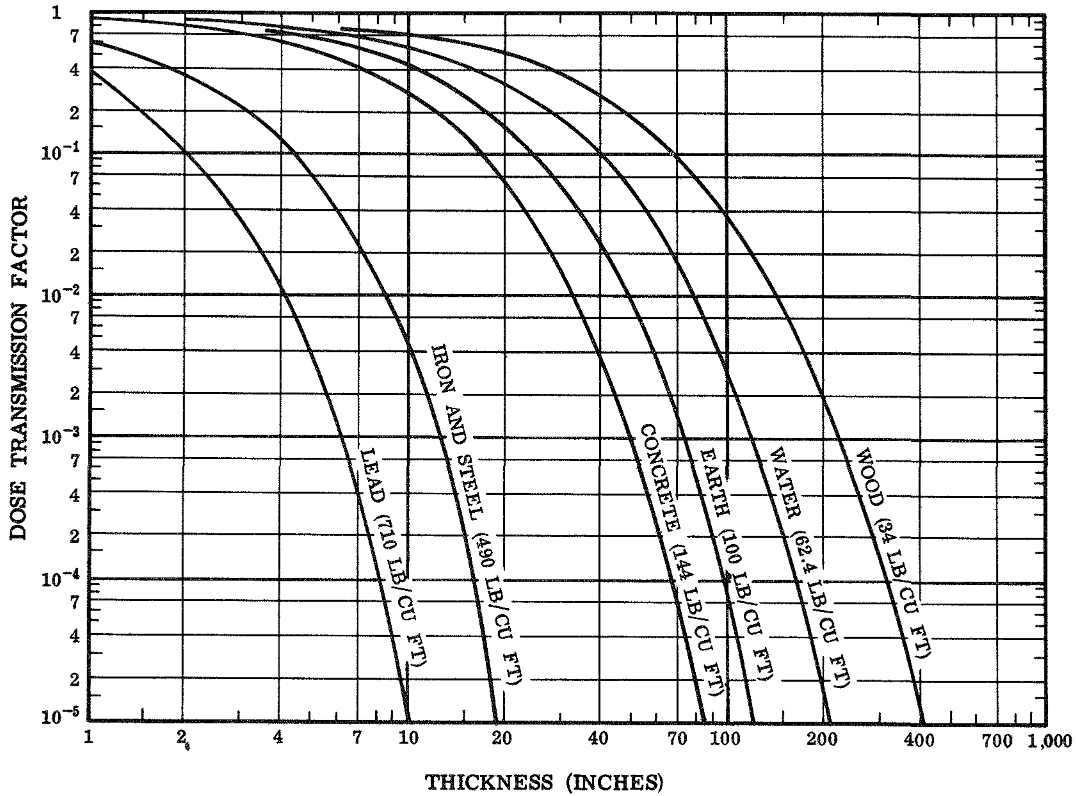

Figure 8.38. Dose transmission factors for initial gamma radiations of various materials as function of thickness.

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EARLY FALLOUT

9.06 The radiological characteristics of the early fallout from a nuclear weapon are those of the fission products and any induced activity produced. The relative importance of these two sources of residual radiation depends upon the percentage of the total yield that is due to fission, and other factors mentioned in § 9.02. There are, however, two additional factors, namely, "fractionation" and "salting" which may affect the activity of the early fallout; these will be described below.

9.07 As the fireball cools, the fission products and other vapors are gradually condensed on such soil and other particles as are sucked up from below while the fireball rises in the air. For detonations over land, where the particles consist mainly of soil minerals, the fission product vapors condense onto both solid and molten soil particles and also onto other particles that may be present. In addition, the vapors of the fission products may condense with vapors of other substances to form mixed solid particles of small size. In these condensation processes the composition of the fission product mixture may be changed by the phenomenon known as "fractionation." The occurrence of fractionation is shown, for example, by the fact that in a land surface burst the larger particles, which fall out of the fireball at early times and are found near ground zero, have different radiological properties from the smaller particles that leave the radioactive cloud at later times and reach the ground some distance downwind.

9.08 The details of the fractionation process are not well understood, but the effect is related, in part at least, to the presence in the early stages of certain fission products which are inherently gaseous, e.g., krypton and xenon. Subsequently, these radioactive gases decay to form rubidium and cesium, respectively, which can condense onto solid particles. Consequently, the first solid particles to fall out, near ground zero, will be depleted not only in krypton and xenon, but also in their various decay (or daughter) products. On the other hand, small particles which have remained in the cloud for some time will have rubidium and cesium, and their daughters, strontium and barium, condensed upon them. Hence, the more distant fallout will be relatively richer in those elements in which the close fallout is depleted.

9.09 An additional phenomenon which contributes to the fractionation of fission product isotopes is the separation of the elements in the ascending fireball as they condense at different times, corresponding to their different boiling points. Thus the refractory elements can

condense at early times in the fireball history, when its temperature is quite high, onto the relatively larger particles which are more abundant at these times. Conversely, volatile elements, with low boiling points, cannot condense until later, when the fireball has cooled and when the larger particle sizes will be depleted. Refractory elements are expected to be relatively more abundant in the close-in early fallout, representing the larger particles, and to be relatively depleted in the more distant portion of the early fallout deposited by smaller particles. The reverse will be true for the more volatile elements. Elements with intermediate boiling points will exhibit behavior between these two extremes.

9.10 For detonations of large energy yield at or near the surface of the sea, where the condensed particles consist of sea-water salts and water, fractionation of the fallout is usually very small. The reason is that the fireball must cool to 100° C (212° F) or less before the evaporated water condenses. The long cooling time and the presence of very small water droplets permit removal from the radioactive cloud of the daughters of the gaseous krypton and xenon along with the other fission products. In this event, there is little or no variation in composition of the radioactive fallout (or rainout) with distance from the explosion.

9.11 The composition of the fallout can also be changed by "salting" the weapon to be detonated. This consists in the inclusion of significant quantities of certain elements, possibly enriched in specific isotopes, for the purpose of producing induced radioactivity. There are several reasons why a weapon might be salted. For example, salting has been used in some weapons tests to provide radioactive tracers for various purposes, such as the study of the paths and relative compositions of the early and delayed stages of fallout. By the choice of elements, to give radioactive products of suitable half lives and radioactivity, the characteristics of the early fallout from a nuclear weapon could be modified for application in radiological warfare (§ 9.110).

Activity and Decay of Early Fallout

9.12 As stated in Chapter I, the fission products constitute a very complex mixture of over 200 different forms (isotopes) of 36 elements. Most of these isotopes are radioactive, decaying by the emission of beta particles, frequently accompanied by gamma radiation. About 2 ounces of fission products are formed for each kiloton (or 125 pounds per megaton) of fission energy yield. The total

radioactivity of the fission products initially is extremely large but it falls off at a fairly rapid rate as the result of radioactive decay (§§ 1.23, 1.57).

9.13 At 1 minute after a nuclear explosion, when the residual nuclear radiation has been postulated as beginning, the gamma-ray activity of the 2 ounces of fission products from a 1-kiloton fission yield explosion is comparable with that of about 30,000 tons of radium in equilibrium with its decay products. It is seen, therefore, that for explosions in the megaton-energy range the amount of radioactivity produced is enormous. Even though there is a decrease from the 1-minute value by a factor of over 3,000 by the end of the day, the radiation intensity will still be large.

9.14 It has been calculated that if all the fission products from an explosion with a 1-megaton fission yield could be spread uniformly over a smooth area of 10,000 square miles, the radiation dose rate after 24 hours would be 6 roentgens per hour at a level of 3 feet above the ground. In actual practice, a uniform distribution would be improbable, since a larger proportion of the fission products would be deposited near ground zero than at farther distances. Hence, the radiation intensity will greatly exceed the average at points near the explosion center, whereas at much greater distances it will usually be less.

9.15 As stated in § 9.01, the early fallout consists mainly, but not entirely, of fission products. An indication of the manner in which the dose rate of the actual mixture decreases with time may be obtained from the following approximate rule: for every seven-fold increase in time after the explosion, the dose rate decreases by a factor of ten. For example, if the radiation dose rate at 1 hour after the explosion is taken as a reference point, then at 7 hours after the explosion the dose rate will have decreased to one-tenth; at $7 \times 7 = 49$ hours (or roughly 2 days) it will be one-hundreth; and at $7 \times 7 \times 7 = 343$ hours (or roughly 2 weeks) the dose rate will be one-thousandth of that at 1 hour after the burst. Another aspect of the rule is that at the end of 1 week (7 days), the radiation dose rate will be one-tenth of the value after 1 day. This rule is accurate to within about 25 percent up to 2 weeks or so and is applicable to within a factor of two up to roughly 6 months after the nuclear detonation. Subsequently, the dose rate decreases at a much more rapid rate than predicted by this rule.

9.16 Information concerning the decrease of dose rate in the early fallout can be obtained from the continuous curve in Figs. 9.16a and b, in which the ratio of the approximate exposure dose rate (in r/hr,

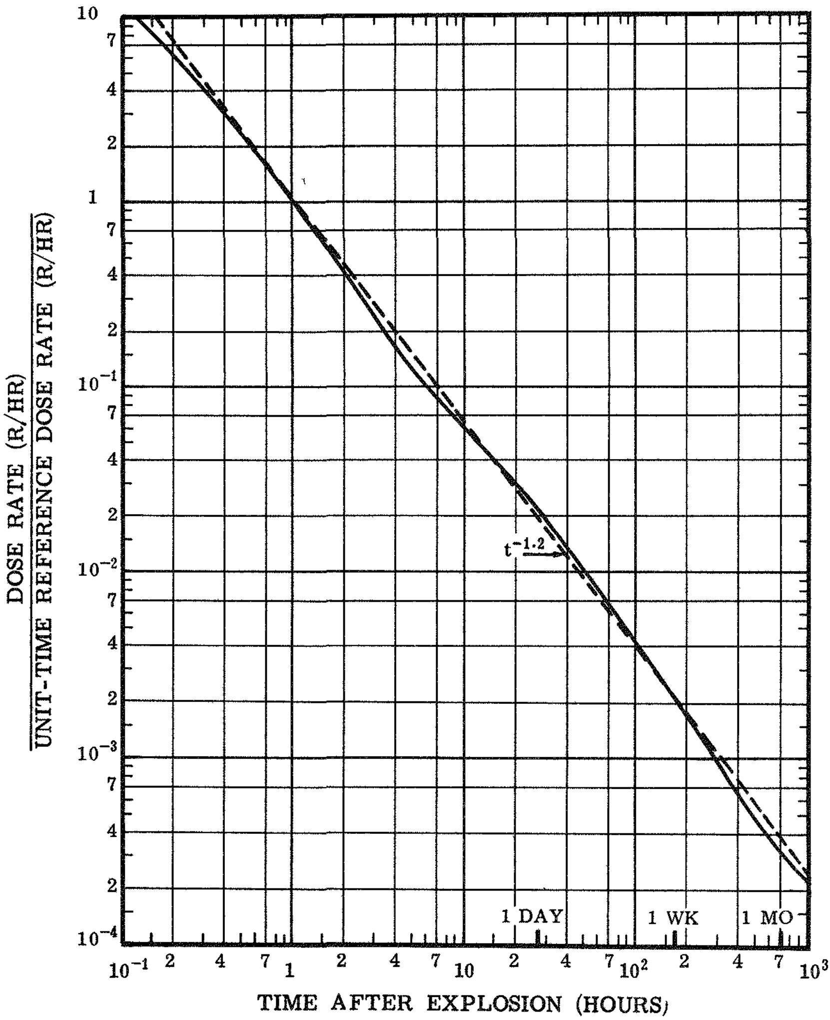

Figure 9.16a. Dependence of dose rate from early fallout upon time after explosion.

i.e., in roentgens per hour) at any time after the explosion to a convenient reference value, called the "unit-time reference dose rate," is plotted against time in hours.[1] The use of the reference dose rate simplifies the representation of the results and the calculations based on them, as will now be shown.

[1] The significance of the dashed lines, marked "$t^{-1.2}$," will be described in § 9.170 *et seq.*, where the physical meaning of the unit-time reference dose rate will be explained. For the present, the dashed lines may be ignored.

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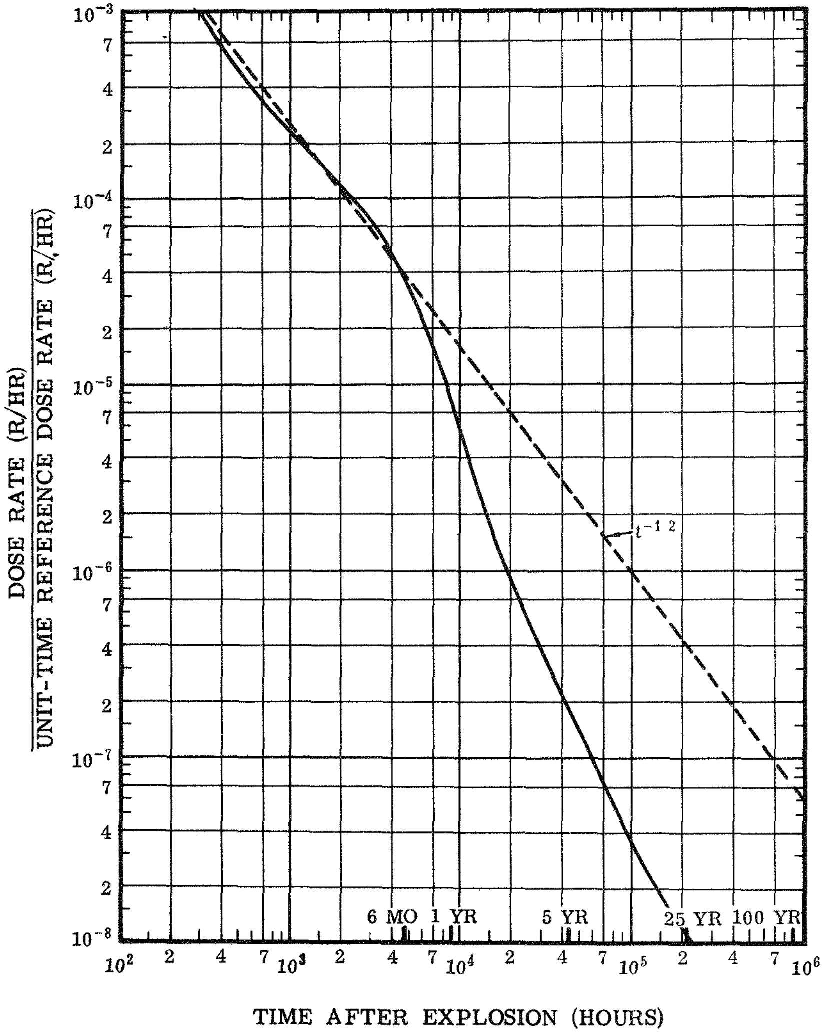

Figure 9.16b. Dependence of dose rate from early fallout upon time after explosion.

9.17 Suppose, for example, that at a given location, the fallout commences at 5 hours after the explosion, and that at 15 hours, when the fallout has ceased to descend, the observed dose rate is 4.0 roentgens per hour. From the curve in Fig. 9.16a (or the data in Table 9.19), it is seen that at 15 hours after the explosion, the ratio of the actual dose rate to the reference value is 0.040; hence, the reference dose rate must be 4.0/0.040=100 roentgens per hour. By means

of this reference value and the decay curves in Figs. 9.16a and b, it is possible to estimate the actual dose rate at the place under consideration at any time after fallout is complete. Thus, if the value is required at 24 hours after the explosion, Fig. 9.16a is entered at the point representing 24 hours on the horizontal axis. Moving upward vertically until the plotted (continuous) line is reached, it is seen that the required dose rate is 0.023 multiplied by the unit-time reference dose rate, i.e., $0.023 \times 100 = 2.3$ roentgens per hour.

9.18 If the dose rate at any time is known, by actual measurement, the value at any other time can be estimated. All that is necessary is to compare the ratios (to the unit-time reference dose rate) for the two given times as obtained from Fig. 9.16a or Fig. 9.16b. For example, suppose the dose rate at 3 hours after the explosion is found to be 50 roentgens per hour; what would be the value at 18 hours? The respective ratios, as given by the curve in Fig. 9.16a, are 0.23 and 0.033, with respect to the unit-time reference dose rate. Hence, the dose rate at 18 hours after the explosion is $50 \times 0.033/0.23 = 7.2$ roentgens per hour.

9.19 The results in Figs. 9.16a and b may be represented in an alternative form, as in Table 9.19, which is more convenient, although somewhat less complete. The dose rate, in any suitable units, is taken as 1,000 at 1 hour after a nuclear explosion; the expected dose rate in the same units at a number of subsequent times, for the same quantity of early fallout, are then as given in the table. If the actual dose rate at 1 hour (or any other time) after the explosion is known, the value at any specified time, up to 1,000 hours, can be obtained by simple proportion.[2]

TABLE 9.19

RELATIVE THEORETICAL DOSE RATES FROM EARLY FALLOUT AT VARIOUS TIMES AFTER A NUCLEAR EXPLOSION

Time (hours)	*Relative dose rate*	*Time (hours)*	*Relative dose rate*
1	1, 000	36	15
1½	610	48	10
2	440	72	6. 2
3	230	100	4. 0
5	130	200	1. 7
6	100	400	0. 70
10	63	600	0. 42
15	40	800	0. 31
24	23	1, 000	0. 24

[2] Several devices, similar to a slide rule, are available for making rapid calculations of the decay of fallout dose rates and related matters.

9.20 It should be noted that Figs. 9.16a and b and Table 9.19 are used for calculations of dose *rates*. In order to determine the actual or total radiation dose received it is necessary to multiply the average dose rate by the exposure time (§ 8.23). However, since the dose rate is steadily decreasing during the exposure, appropriate allowance for this must be made. The results of the calculations based on Fig. 9.16a are expressed by the curve in Fig. 9.20. It gives the total dose received from early fallout, between 1 minute and any other specified time after the explosion, in terms of the unit-time reference dose rate.

9.21 To illustrate the application of Fig. 9.20, suppose that an individual becomes exposed to a certain quantity of gamma radiation from early fallout 2 hours after a nuclear explosion and the dose rate, measured at that time, is found to be 1.5 roentgens per hour. What will be the total dose received during the subsequent 12 hours, i.e., by 14 hours after the explosion? The first step is to determine the unit-time reference dose rate. From Fig. 9.16a it is seen that

$$\frac{\text{Dose rate at 2 hours after explosion}}{\text{Unit-time reference dose rate}}=0.40$$

and, since the dose rate at 2 hours is known to be 1.5 roentgens per hour, the reference value is $1.5/0.40=3.8$ roentgens per hour. Next, from Fig. 9.20, it is found that for 2 hours and 14 hours, respectively, after the explosion,

$$\frac{\text{Total dose at 2 hours after explosion}}{\text{Unit-time reference dose rate}}=5.8$$

and

$$\frac{\text{Total dose at 14 hours after explosion}}{\text{Unit-time reference dose rate}}=7.1.$$

Hence, by subtraction

$$\frac{\text{Dose received between 2 and 14 hours after explosion}}{\text{Unit-time reference dose rate}}=1.3.$$

The unit-time reference dose rate is 3.8 roentgens per hour, and so the total dose received in the 12 hours, between 2 and 14 hours after the explosion, is $3.8\times1.3=4.9$ roentgens.

9.22 The percentage of the "infinity (residual radiation) dose" that would be received from a given quantity of early fallout, computed from 1 minute to various times after a nuclear explosion, is

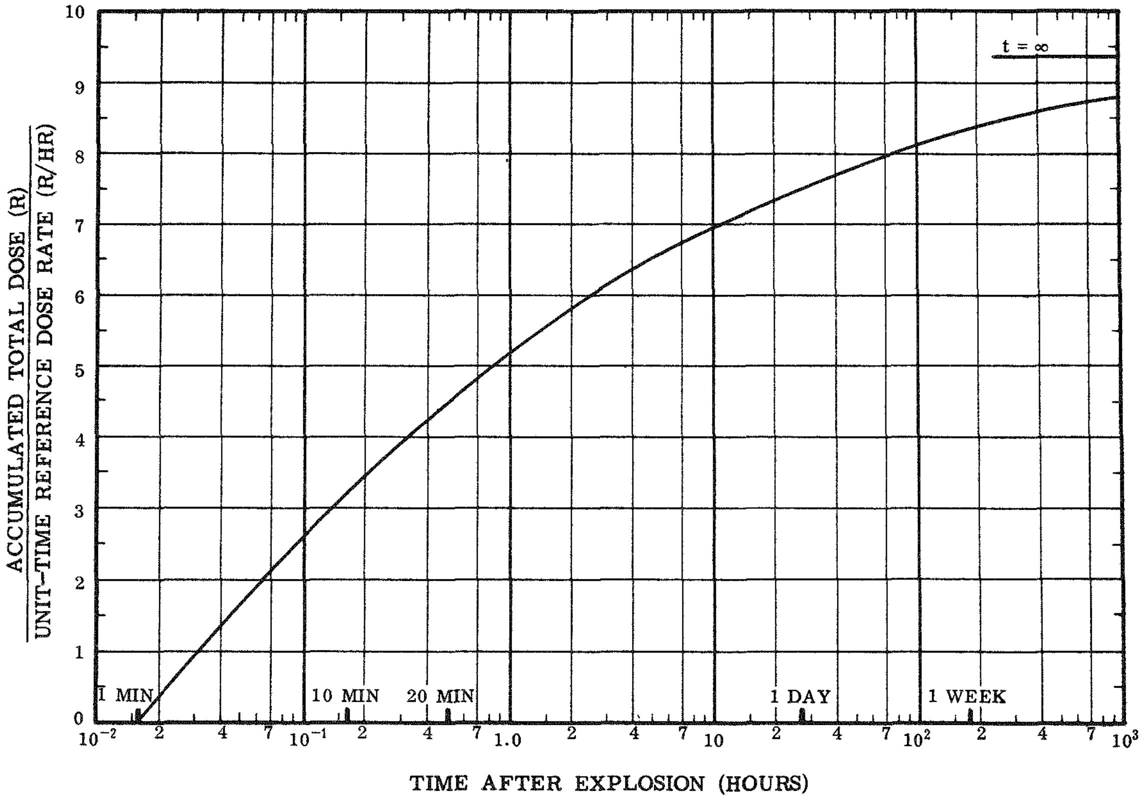

Figure 9.20. Curve for determining total dose from early fallout at various times after explosion.

shown in Table 9.22. The infinity dose is essentially that which would be received as a result of continued exposure to a certain quantity of early fallout for many years. These data can be used to determine the proportion of the infinity dose received during any specified period following the complete deposition of the early fallout from a nuclear explosion.

TABLE 9.22

PERCENTAGES OF INFINITY RESIDUAL RADIATION DOSE RECEIVED FROM 1 MINUTE UP TO VARIOUS TIMES AFTER EXPLOSION

Time (hours)	*Percent of infinity dose*	*Time (hours)*	*Percent of infinity dose*
1	55	72	86
2	62	100	88
4	68	200	90
6	71	500	93
12	75	1, 000	95
24	80	2, 000	97
48	83	10, 000	99

9.23 For example, if an individual is exposed to a certain amount of early fallout during the interval from 2 hours to 14 hours after the explosion, the percentage of the infinity dose received may be obtained by subtracting the respective values in (or estimated from) Table 9.22, i.e., 76 (for 14 hours) minus 62 (for 2 hours), giving 14 percent, i.e., 0.14, of the infinity dose. The actual value of the infinity dose computed from 1 minute after detonation, is 9.3 times the unit-time reference dose rate (in roentgens per hour), as shown in Fig. 9.20. Hence, if the reference value is 3.8 roentgens per hour as in the above example, the dose received between 2 hours and 14 hours after the burst is $0.14 \times 9.3 \times 3.8 = 4.9$ roentgens, as before.

9.24 With the aid of Figs. 9.16 a and b and Fig. 9.20 (or the equivalent Tables 9.19 and 9.22) many different types of calculations relating to radiation dose rates and total doses received from early fallout can be made. The procedures can be simplified, however, by means of special charts, as will be shown below. The results, like those given above, are applicable to a particular quantity of fallout. If there is any change in the situation, either by further contamination or by decontamination, the conclusions will not be valid.

9.25 If the radiation dose rate from early fallout is known at a given location, Fig. 9.25 may be used to determine the dose rate at any other time at the same location, assuming there has been no change in the fallout other than natural radioactive decay. The same nomo-

graph can be utilized, alternatively, to determine the time after the explosion at which the dose rate will have attained a specified value. It should be mentioned that the nomograph is based on the straight line marked "$t^{-1.2}$" in Figs. 9.16 a and b which is seen to deviate slightly from the theoretical decay curve. Nevertheless, it is possible to obtain from Fig. 9.25 approximate dose rates, which are within 25 percent of the theoretical decay values of Figs. 9.16 a and b for the first 200 days after the nuclear detonation.

9.26 To determine the total radiation dose received during a specified time of stay in an area contaminated with early fallout, if the dose rate in that area at any given time is known, use is made of Fig. 9.26 in conjunction with Fig. 9.25. The chart may also be employed to evaluate the time when a particular operation may be commenced in a contaminated area in order not to exceed a certain total radiation dose.

9.27 Another type of calculation of radiation dose in a contaminated area is based on a knowledge of the dose rate at the time of entry into that area. The procedure described in the examples facing Fig. 9.26, which also requires the use of Fig. 9.25, may then be applied to determine either the total dose received in a specified time of stay or the time required to accumulate a given dose of radiation. The calculation may, however, be simplified by means of Fig. 9.27 which avoids the necessity for evaluating the unit-time reference dose rate, provided the dose rate at the time of entry into the contaminated area is known.

9.28 If the whole of the early fallout reached a given area within a short time, Fig. 9.27 could be used to determine how the total radiation dose received by inhabitants of that area would increase with time, assuming no protection. For example, suppose the early fallout arrived at 6 hours after the explosion and the dose rate at that time was R roentgens per hour; the total dose received would be $9R$ roentgens in 1 day, $12R$ roentgens in 2 days, and $16R$ roentgens in 5 days.

9.29 It is evident that the first day or so after the explosion is the most hazardous as far as the exposure to residual nuclear radiation from the early fallout is concerned. Although the particular values given above apply to the case specified, i.e., complete early fallout arrival 6 hours after the explosion, the general conclusions to be drawn are true in all cases. The radiation doses that would be received during the first day or two are considerably greater than on subsequent days. Consequently, it is in the early stages following the explosion that protection from fallout is most important.

(Text continued on p. 432)

The nomograph in Fig. 9.25 gives an approximate relationship between the dose rate at any time after the explosion and the unit-time reference value. If the dose rate at any time is known, that at any other time can be derived from the figure. Alternatively, the time after the explosion at which a specific dose rate is attained can be determined approximately.

For the conditions of applicability of Fig. 9.25, see §9.30.

Example

Given: The radiation dose rate due to fallout at a certain location is 8 roentgens per hour at 6 hours after a nuclear explosion.

Find: (*a*) The dose rate at 24 hours after the burst.
(*b*) The time after the explosion at which the dose rate is 1 roentgen per hour.

Solution: By means of a ruler (or straight edge) join the point representing 8 roentgens per hour on the left scale to the time 6 hours on the right scale. The straight line intersects the middle scale at 70 roentgens per hour; this is the unit-time reference value of the dose rate.

(*a*) Using the straight edge, connect this reference point (70 r/hr) with that representing 24 hours after the explosion on the right scale, and extend the line to read the corresponding dose rate on the left scale, i.e., 1.5 roentgens per hour. *Answer*

(*b*) Extend the straight line joining the dose rate of 1 roentgen per hour on the left scale to the reference value of 70 roentgens per hour on the middle scale out to the right scale. This is intersected at 34 hours after the explosion. *Answer*

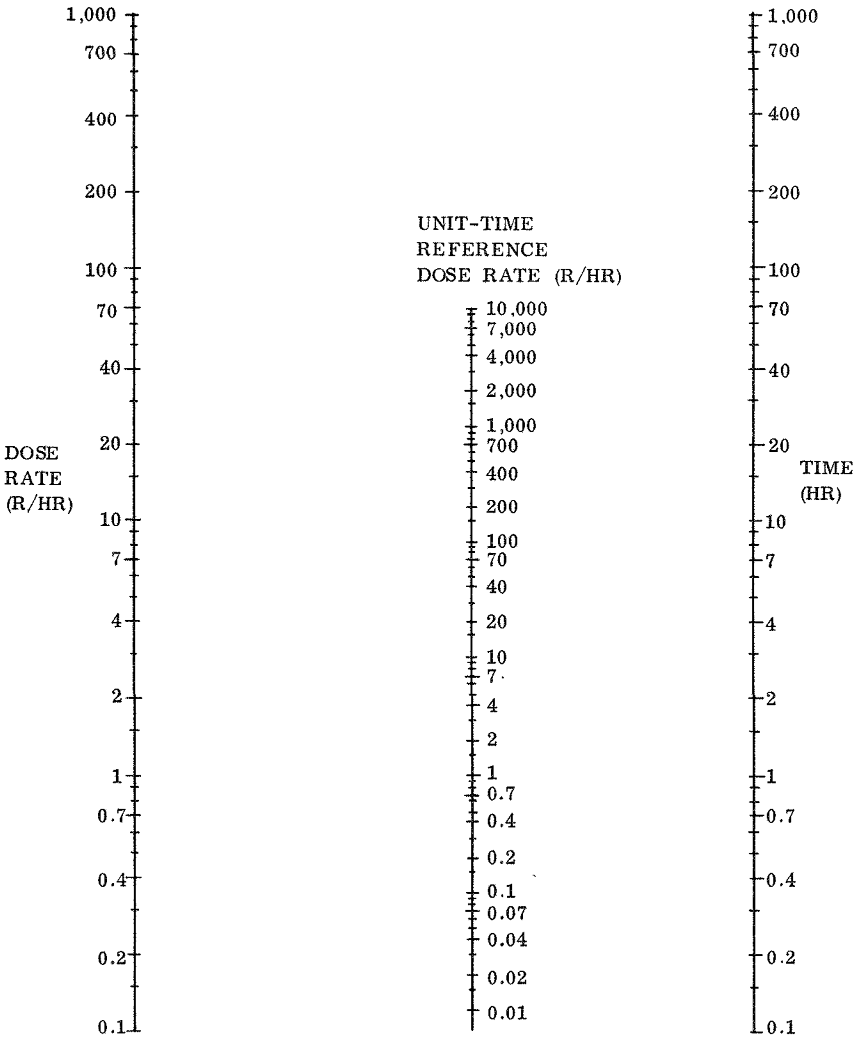

Figure 9.25. Nomograph for calculation of approximate dose rates from early fallout.

From Fig. 9.26 the total radiation dose received from early fallout during any specified stay in a contaminated area can be estimated if the dose rate at some definite time after the explosion is known. Alternatively, the time can be calculated for commencing an operation requiring a specified stay and a prescribed total radiation dose.

For conditions of applicability of Fig. 9.26, see § 9.30.

Example

Given: The dose rate at 4 hours after a nuclear explosion is 6 roentgens per hour.

Find: (*a*) The total dose received during a period of 2 hours commencing at 6 hours after the explosion.

(*b*) The time after the explosion when an operation requiring a stay of 5 hours can be started if the total dose is to be 4 roentgens.

Solution: The first step is to determine the unit-time reference dose rate (R_1). From Fig. 9.25, a straight line connecting 6 roentgens per hour on the left scale with 4 hours on the right scale intersects the middle scale at 32 roentgens per hour; this is the value of R_1.

(*a*) Enter Fig. 9.26 at 6 hours after the explosion (horizontal scale) and move up to the curve representing a time of stay of 2 hours. The corresponding reading on the vertical scale, which gives the multiplying factor to convert R_1 to the required total dose, is seen to be 0.19. Hence, the total dose received is

$$0.19 \times 32 = 6.1 \text{ roentgens.} \quad \textit{Answer}$$

(*b*) Since the total dose is given as 4 roentgens and R_1 is 32 roentgens per hour, the multiplying factor is $4/32 = 0.125$. Entering Fig. 9.26 at this point on the vertical scale and moving across until the (interpolated) curve for 5 hours stay is reached, the corresponding reading on the horizontal scale, giving the time after the explosion, is seen to be 21 hours. *Answer*

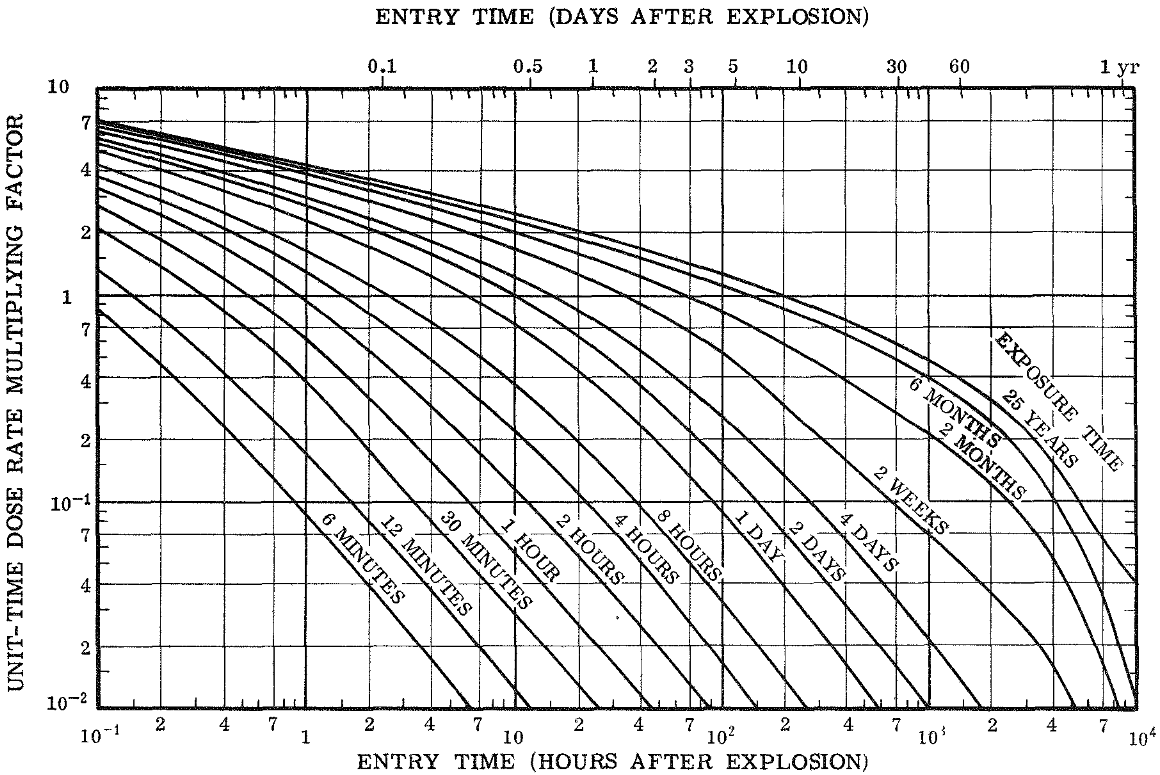

Figure 9.26. Total radiation dose from early fallout based on unit-time reference dose rate.

From the chart in Fig. 9.27, the total radiation dose received from early fallout during any specified stay in a contaminated area can be estimated if the dose rate at the time of entry into the area is known. Alternatively, the time of stay may be evaluated if the total dose is prescribed.

For conditions of applicability of Fig. 9.27, see §9.30.

Example

Given: Upon entering a contaminated area at 12 hours after a nuclear explosion the dose rate is 5 roentgens per hour.

Find: (*a*) The total radiation dose received for a stay of 2 hours.

(*b*) The time of stay for a total dose of 20 roentgens.

Solution: (*a*) Start at the point on Fig. 9.27 representing 12 hours after the explosion on the horizontal scale and move up to the curve representing a time of stay of 2 hours. The multiplying factor for the dose rate at the time of entry, as read from the vertical scale, is seen to be 1.9. Hence, the total dose received is

$$1.9 \times 5 = 9.5 \text{ roentgens.} \quad \textit{Answer.}$$

(*b*) The total dose is 20 roentgens and the dose rate at the time of entry is 5 roentgens per hour; hence, the multiplying factor is 20/5 =4.0. Enter Fig. 9.27 at the point corresponding to 4.0 on the vertical scale and move horizontally to meet a vertical line which starts from the point representing 12 hours after the explosion on the horizontal scale. The two lines are found to intersect at a point indicating a time of stay of about 4½ hours. *Answer.*

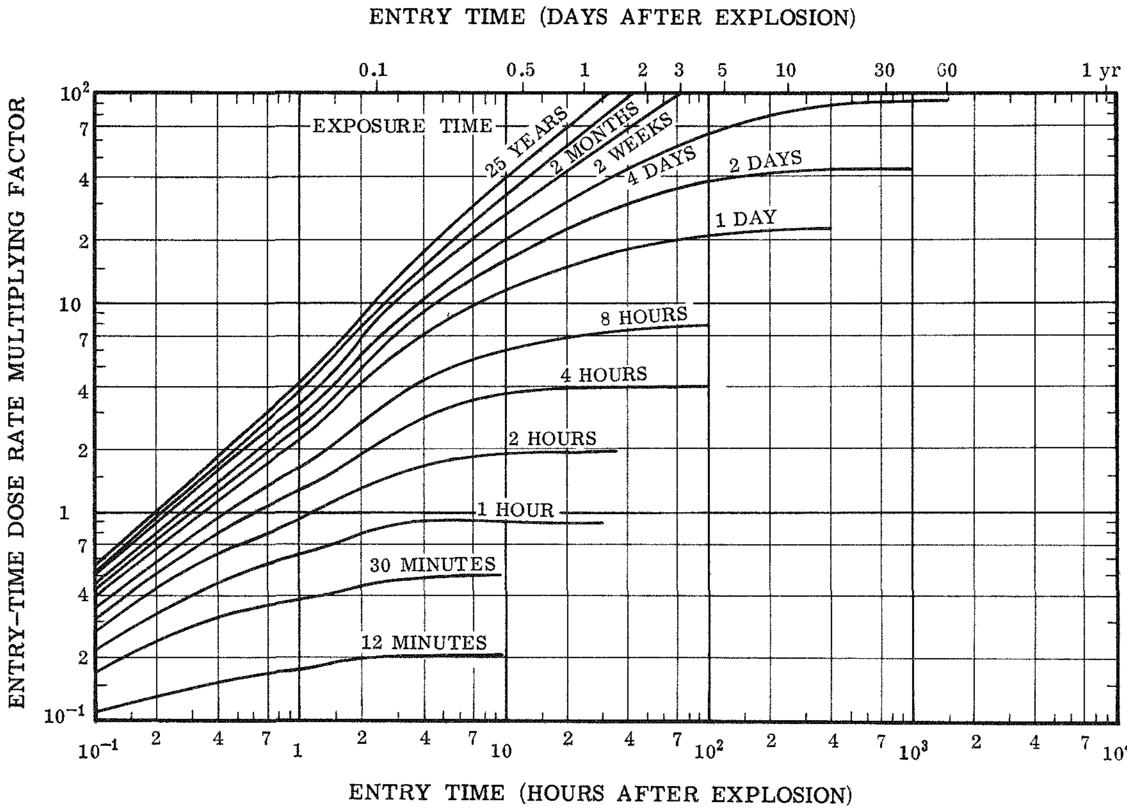

Figure 9.27. Total radiation dose from early fallout based on dose rate at time of entry.

(Text continued from p. 425.)

9.30 It is essential to understand that the tables and figures given above, and the calculations of radiation dose rates and doses in which they are used, are based on the assumption that an individual is exposed to a certain quantity of early fallout and remains exposed continuously (without protection) to this same quantity for a period of time. In an actual fallout situation, however, these conditions probably would not exist. For one thing, any shelter which attenuates the radiation will reduce the exposure dose rate (and dose) as given by the calculations. Furthermore, the action of wind and weather will generally tend to disperse the fallout particles in some areas and concentrate them in others. As a result, there may be a change in the quantity of early fallout at a given location during the time of exposure; the radiation dose rate (and dose) would then change correspondingly. The same would be true, of course, if there were additional fallout from another nuclear explosion.

Neutron-Induced Activity

9.31 The neutrons liberated in the fission process, but which are not involved in the propagation of the fission chain, are ultimately captured by the weapon materials through which they must pass before they can escape, by nitrogen (especially) and oxygen in the atmosphere, and by various elements present in the earth's surface. As a result of capturing neutrons many substances become radioactive. They, consequently, emit beta particles, frequently accompanied by gamma radiation, over an extended period of time following the explosion. Such neutron-induced activity, therefore, is part of the residual nuclear radiation.

9.32 The activity induced in the weapon materials is highly variable, since it is greatly dependent upon the design or structural characteristics of the weapon. Any radioactive isotopes produced by neutron capture in the residues will remain associated with the fission products. The curves and tables given above have been adjusted to include the contribution of such isotopes, e.g., uranium-237 and -239 and neptunium-239 and -240. In the period from 20 hours to 2 weeks after the burst, depending to some extent upon the weapon materials, these isotopes can contribute up to 40 percent of the total activity of the weapon residues. At other times, their activity is negligible in comparison with that of the fission products.

9.33 When neutrons are captured by oxygen and nitrogen nuclei present in the atmosphere, the resulting activity is of little or no significance, as far as the early residual radiation is concerned. Oxy-

gen, for example, interacts to a slight extent with fast neutrons, but the product, an isotope of nitrogen, has a half-life of only 7 seconds. It will thus undergo almost complete decay within a minute or two.

9.34 The radioactive product of neutron capture by nitrogen is carbon-14 (§ 8.89) which emits beta particles of relatively low energy but no gamma rays. Although carbon-14 has a long half-life (5,760 years) and is not highly active, in the form of carbon dioxide it is readily incorporated by all forms of plant life and thus finds its way into the human body. The carbon in all living organisms contains a certain proportion of carbon-14 resulting from the capture by atmospheric nitrogen of neutrons from naturally occurring cosmic rays. The total reservoir of carbon-14 in nature, including oceans, atmosphere, and biosphere (living organisms), is known to be from 50 to 80 tons; of this amount, about 1 ton is in the atmosphere and 0.2 ton in the biosphere. It is estimated that before September 1961, weapons testing had produced 0.65 ton of carbon-14 and about half had dissolved in the oceans. Consequently, the carbon-14 content of the atmosphere had been increased by about 30 percent over the normal (1950) value. In the course of time, more and more of the carbon-14 will enter the oceans and, provided there is no great addition as a result of weapons tests, the level in the atmosphere will fall to less than 1 percent above normal in 50 to 100 years.

9.35 An important contribution to the residual nuclear radiation can arise from the activity induced by neutron capture in certain elements in the earth and in sea water. The extent of this radioactivity is highly variable. The element which probably deserves most attention, as far as environmental neutron-induced activity is concerned, is sodium. Although this is present only to a small extent in average soils, the amount of radioactive sodium-24 formed by neutron capture can be quite appreciable. This isotope has a half-life of 15 hours and emits both beta particles, and more important, gamma rays of relatively high energy.[3]

9.36 Another source of induced activity is manganese which, being an element that is essential for plant growth, is found in most soils, even though in small proportions. As a result of neutron capture, the radioisotope manganese-56, with a half-life of 2.6 hours, is formed. It gives off several gamma rays of high energy, in addition to beta particles, upon decay. Because its half-life is less than that of sodium-24, the manganese-56 loses its activity more rapidly. But, within the

[3] In each act of decay of sodium-24, there are produced two gamma-ray photons, with energies of 1.4 and 2.8 Mev, respectively. The mean energy per photon from fission products at 1 hour after formation is about 1 Mev.

first few hours after an explosion, the manganese may constitute a serious hazard, greater than that of sodium.

9.37 A major constituent of soil is silicon, and neutron capture leads to the formation of radioactive silicon-31. This isotope, with a half-life of 2.6 hours, gives off beta particles, but gamma rays are emitted in not more than about 0.07 percent of the disintegrations. It will be seen later that only in certain circumstances do beta particles themselves constitute a serious radiation hazard. Aluminum, another common constituent of soil, can form the radioisotope aulminum-28, with a half-life of only 2.3 minutes. Although isotopes such as this, with short half-lives, contribute greatly to the high initial activity, very little remains within an hour after the nuclear explosion.

9.38 When neutrons are captured by the hydrogen nuclei in water, the product is the nonradioactive (stable) isotope, deuterium, so that there is no resulting activity. As seen in § 9.33, the activity induced in oxygen can be ignored because of the very short half-life of the product. However, substances dissolved in the water, especially the salt (sodium chloride) in sea water, can be sources of considerable induced activity. The sodium produces sodium-24, as already mentioned, and the chlorine yields chlorine-38 which emits both beta particles and high-energy gamma rays. However, the half-life of chlorine-38 is only 37 minutes, so that within 4 to 5 hours its activity will have decayed to about 1 percent of its initial value.

9.39 Apart from the interaction of neutrons with elements present in soil and water, the neutrons from a nuclear explosion may be captured by other nuclei, such as those contained in structural and other materials. Among the metals, the chief sources of induced radioactivity are probably zinc, copper, and manganese, the latter being a constituent of many steels, and, to a lesser extent, iron. Wood and clothing are unlikely to develop appreciable activity as a result of neutron capture, but glass could become radioactive because of the large proportions of sodium and silicon. Foodstuffs can acquire induced activity, mainly as a result of neutron capture by sodium. However, at such distances from a nuclear explosion and under such conditions that this activity would be significant, the food would probably not be fit for consumption for other reasons, e.g., blast and fire damage. Some elements, e.g., boron, absorb neutrons without becoming radioactive, and their presence will decrease the induced activity.

Uranium and Plutonium

9.40 The uranium and plutonium which may have escaped fission in the nuclear weapon represent a further possible source of residual

nuclear radiation. The fissionable isotopes of these elements emit alpha particles and also some gamma rays of low energy. However, because of their very long half-lives, the activity is very small compared with that of the fission products.

9.41 It will be seen later (§ 9.130) that the alpha particles from uranium and plutonium, or from radioactive sources in general, are completely absorbed in an inch or two of air. This, together with the fact that the particles cannot penetrate ordinary clothing, indicates that uranium and plutonium deposited on the earth do not represent a serious external hazard. Even if they actually come in contact with the body, the alpha particles emitted are unable to penetrate the unbroken skin.

9.42 Although there is negligible danger from uranium and plutonium outside the body, it is possible for dangerous amounts of these elements to enter the body through the lungs, the digestive system, or breaks in the skin. Plutonium, for example, tends to concentrate in bone, where the prolonged action of the alpha particles can cause serious harm.

9.43 At one time it was suggested that the explosion of a sufficiently large number of nuclear weapons might result in such an extensive distribution of the plutonium as to represent a worldwide hazard. It is now realized that the fission products—the radioisotope strontium-90 in particular—are a more serious hazard than plutonium is likely to be. Further, any steps taken to minimize the danger from fission products, which are much easier to detect, will automatically take care of the plutonium. Some reference to the behavior of this element in the body will be made in Chapter XI.

Clean and Dirty Weapons

9.44 The terms "clean" and "dirty" are often used to describe the amount of radioactivity produced by a fusion weapon (or hydrogen bomb) relative to that from what might be described as a "normal" weapon. The latter may be defined as one in which no special effort has been made either to increase or to decrease the amount of radioactivity produced for the given explosion yield. A "clean" weapon would then be one which is designed to yield significantly less radioactivity than an equivalent normal weapon. It should be noted, however, that a clean fusion weapon would inevitably produce some radioactive species. Even if a pure fusion weapon, with no fission, should be developed, its explosion in air would still result in the formation of carbon-14 and possibly other neutron-induced

activities. If special steps were taken in the design of a fusion device, e.g., by salting (§ 9.11), so that upon detonation it generated more radioactivity than a similar normal weapon, it would be described as "dirty." By its very nature, a fission weapon must be regarded as being dirty.

DISTRIBUTION OF EARLY FALLOUT

Modes of Contamination

9.45 There are two main ways in which the earth's surface can become contaminated with radioactive material as a result of a nuclear explosion. One is by the induced activity following the capture of neutrons by various elements present in the soil (or sea), and the other is by the fallout, that is, by the descent of radioactive particles from the column and cloud formed in the explosion (§ 2.18). The amount of contamination and its distribution over the earth's surface are principally dependent upon the energy yield of the explosion, the relative contributions of fission and fusion to the total yield, the height of burst, the nature of the surface over (or on) which the detonation occurs, and, finally, the meteorological conditions.

9.46 An air burst, by definition, is one taking place at such a height above the earth that no appreciable quantities of surface materials are taken up into the fireball. The radioactive residues of the weapon then condense into extremely small particles which remain suspended in the atmosphere for a long time. Hence, except possibly under special meteorological conditions, there will be no early (or local) fallout. However, depending on the characteristics of the weapon, the height of burst, and the nature of the surface there will be more or less contamination, in the general vicinity of ground zero, as a result of radioactivity induced by neutron capture. The contamination which might arise in this manner is highly variable, but it is probable that, apart from strong underground structures, the area affected would be completely devastated by blast and fire.

9.47 As the height of burst decreases, and earth, dust, and other debris from the earth's surface are taken up into the fireball, an increasing proportion of the fission (and other radioactive) products of the nuclear explosion condense onto particles of appreciable size. These contaminated particles range in diameter from less than 1 micron (see § 2.27, footnote) to several millimeters; the larger ones begin to fall back to earth even before the radioactive cloud has at-

tained its maximum height, whereas the very smallest ones may remain suspended in the atmosphere for long periods. In these circumstances there will be an early fallout, with the larger particles reaching the ground within 24 hours.

9.48 The proportion of the total radioactivity of the weapon residues that is present in the early fallout, sometimes called the "early fallout fraction," appears to vary from one test explosion to another. For land surface bursts the early fallout fraction has been estimated to range from 50 to 70 percent. Values somewhat higher than this are expected from shallow underground bursts, whereas for water surface bursts the value is lower, in the neighborhood of 30 percent. Some variability is expected in the fallout fraction for a given type of burst due to variation in environmental and meteorological conditions. Nevertheless, it will be assumed here that 60 percent of the total radioactivity from a land surface burst weapon will be in the early fallout (§ 9.184). The remaining 40 percent will eventually reach the earth in the delayed fallout, most of it many hundreds or thousands of miles away (§ 9.141 *et seq.*).

Distribution of Contamination

9.49 The distribution on the ground of the activity from the early fallout, even for similar nuclear yields, also shows great variability. In addition to the effect of wind, such factors as the dimensions of the radioactive cloud, the distribution of radioactivity within the mushroom head, and the range of particle sizes contribute to the uncertainty in attempts to predict the fallout pattern.

9.50 The spatial distribution of radioactivity within the cloud is not known accurately, but some of the gross features have been derived from observations and theoretical considerations. It is generally accepted that the mushroom head from a land surface burst contains about 90 percent of the total activity with the remainder residing in the stem. The proportion of activity in the stem may be even less for a water surface burst and almost zero for an air burst. However, it appears that some radioactive particles from the mushroom head fall or are transported by subsiding air currents to lower altitudes even before the cloud reaches its maximum height. There is some evidence that, for explosions in the megaton range, the highest concentration of radioactivity initially lies in the lower third of the head of the mushroom cloud. It is probable, too, that in detonations of lower yield, a layer of relatively high activity exists somewhere in the cloud. However, the location of the peak concentration appears

to vary with different detonations, perhaps as a function of atmospheric conditions.

9.51 Because particles of different sizes descend at different rates and carry different amounts of radioactive contamination, the fallout pattern will depend markedly on the size distribution of the particles in the cloud after condensation has occurred. In general, larger particles fall more rapidly and carry more activity, so that a high proportion of such particles will lead to greater contamination near ground zero, and less at greater distances, than would be the case if small particles predominated.

9.52 The particle size distribution in the radioactive cloud may well depend on the nature of the material which becomes engulfed by the fireball. A surface burst in a city for example, could result in a particle size distribution, and consequent fallout pattern, which would differ from those produced under test conditions in Nevada and the Pacific. However, in the absence of any definite evidence to the contrary it is generally assumed that the fallout pattern for a surface burst in a large city will not differ greatly from those associated with surface and tower shots in the Nevada desert.

Area of Contamination

9.53 The largest particles fall to the ground from the radioactive cloud and stem shortly after the explosion and hence are found within a short distance of surface zero. Smaller particles, on the other hand, will require many hours to fall to earth. During this period they may be carried hundreds of miles from the burst point by the prevailing winds. The very smallest particles have no appreciable rate of fall and so they may circle the earth many times before reaching the ground, generally in precipitation with rain or snow.

9.54 The fact that small particles from the radioactive cloud may reach the ground at considerable distances from the explosion means that fallout from a surface burst can produce serious contamination far beyond the range of other effects, such as blast, shock, thermal radiation, and initial nuclear radiation. It is true that the longer the cloud particles remain suspended in the air, the less will be their activity when they reach the ground. However, the total quantity of contaminated material produced by the surface burst of a megaton weapon with a high fission yield is so large that fallout may continue to arrive in hazardous concentrations up to perhaps 24 hours after the burst. Radioactive contamination from a single deto-

nation may thus affect vast areas and so fallout must be regarded as one of the major effects of nuclear weapons.

9.55 An important factor determining the area covered by appreciable fallout, as well as its distribution within that area, is the wind pattern from the ground up to the top of the radioactive cloud. The direction and speed of the wind at the cloud level will influence the motion and extent of the cloud itself. In addition, the winds at lower altitudes, which may change both in time and space, will cause the fallout particles to drift one way or another while they descend to earth. The situation may be further complicated by the effect of rain and of irregularities in the terrain. These, as well as irregular distribution of activity in the cloud and fluctuations in the wind speed and direction, will contribute to the development of "hot spots" of much higher activity than in the immediate surroundings.

Fallout Patterns

9.56 Information concerning fallout distribution has been obtained from observations made during nuclear weapons tests at the Nevada Test Site and the Eniwetok Proving Grounds. However, there are many difficulties in the analysis and interpretation of the results, and their use to predict the situation that might arise from a land surface burst over a large city. This is particularly the case for the megaton-range detonations at the Eniwetok Proving Grounds. Since the fallout descends over vast areas of the Pacific Ocean, the contamination pattern of a large area must be inferred from a relatively few radiation dose measurements (§ 9.101). Furthermore, the presence of sea water affects the results, as will be seen below.

9.57 Nuclear tests in Nevada have been confined to weapons having yields below 100 kilotons and most of the detonations were at the tops of steel towers 100 to 700 feet high or from balloons at levels of 400 to 1,500 feet. None of these could be described as a true surface burst and, in any event, in the tower shots there is evidence that the fallout was affected by the tower. There have been a few surface bursts, but the energy yields were about 1 kiloton or less, so that they provided relatively little useful information concerning the effects to be expected from weapons of higher energy. Tests of fusion weapons with yields up to 15 megatons TNT equivalent have been made at the Eniwetok Proving Grounds. A very few were detonated on atoll islands, but most of the shots were fired on barges in the lagoons or on coral reefs. In all cases, however, considerable quantities of sea water were drawn into the radioactive

cloud, so that the fallout was probably quite different from what would have been associated with a true land surface burst.

9.58 The irregular nature of the fallout distribution is shown by the patterns in Figs. 9.58 a and b; the lines are drawn through points having the indicated dose rates at 12 hours after the detonation time. Figure 9.58a refers to the BOLTZMANN shot (12 kilotons, 500-foot tower) of May 28, 1957 and Fig. 9.58b to the TURK shot (43 kilotons, 500-foot tower) of March 7, 1955. Because of the difference in wind conditions, the patterns are quite different. Furthermore, attention should be drawn to the hot spot, some 60 miles NNW of the northern boundary of the Nevada Test Site, that was observed in connection with the BOLTZMANN test. This area was found to be seven times more radioactive than its immediate surroundings. The location was immediately downwind of a mountain range and rain was reported in the general vicinity at the time the fallout occurred. Either or both of these factors may have been responsible for the increased radioactivity.

9.59 Measurement of fallout activity from megaton-yield weapons in the Pacific Ocean area has indicated the presence of marked irregularities in the overall pattern. Some of these may have been due to the difficulties involved in collecting and processing the limited data. Nevertheless, there is evidence to indicate that a hot spot some distance (50 to 75 miles) downwind of the burst point may be typical of the detonations at the Eniwetok Proving Grounds and, in fact, some fallout prediction methods have been designed to reproduce this feature. Whether a similar hot spot would appear following a land surface burst is quite uncertain.

Prediction of Fallout Patterns

9.60 Several methods, of varying degree of complexity, have been developed for predicting dose rates and integrated (total) doses resulting from fallout. These methods fall into four general categories; they are, in decreasing order of complexity, and hence detail, the mathematical fallout model, the idealized fallout pattern, the danger sector forecast, and the analog method. Each of these techniques requires, of course, a knowledge of the total and fission yields of the explosion, the burst height, and the wind structure to the top of the radioactive cloud in the vicinity of the burst.

9.61 In the fallout model method, an attempt is made to describe fallout mathematically and, with various inherent assumptions, to predict the dose-rate contours resulting from a particular situation.

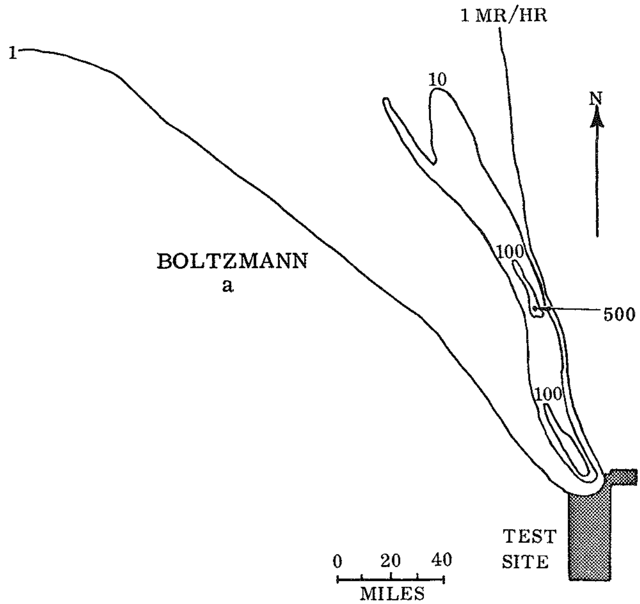

Figure 9.58a. Early fallout dose-rate contours from the BOLTZMANN shot at the Nevada Test Site.

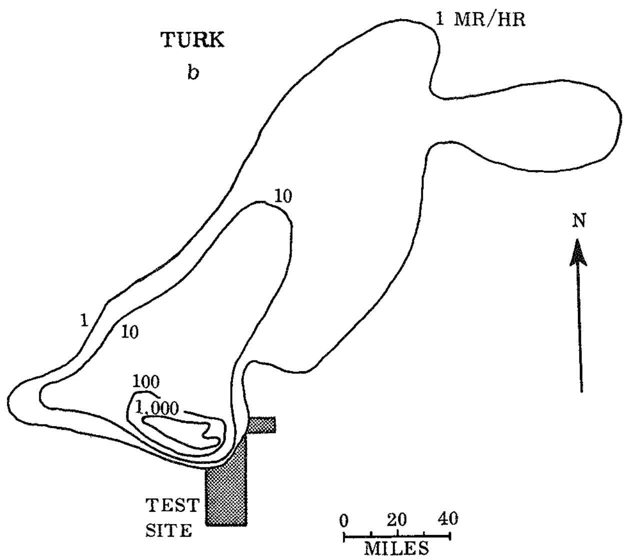

Figure 9.58b. Early fallout dose-rate contours from the TURK shot at the Nevada Test Site.

Most of the procedures are so complex as to require the use of a digital computer in their application to a variety of circumstances. They are, consequently, employed primarily in theoretical studies of the fallout process, in making planning estimates, and in the preparation of templates for use with analog prediction methods. Less detailed mathematical models which do not require the use of digital computers have been used to predict fallout patterns during nuclear tests.

9.62 The analog technique, which is essentially a comparison process, utilizes a pattern chosen from a catalog of fallout patterns covering a wide range of yields and wind conditions. The choice is determined by the similarity between the yield and wind in the given situation and those in the catalog pattern. The catalog can consist of actual fallout patterns and others interpolated and extrapolated from these, or of patterns obtained by calculation from a mathematical fallout model.

9.63 The danger sector forecast requires a minimum of detailed information in order to give a qualitative picture of the general fallout area and an idea of the arrival times. Although it provides a rough indication of the relative degree of hazard, there is little or no information concerning the actual dose rates to be expected at various locations. The method yields a prediction quickly and simply and is probably as accurate as the explosion yield and meteorological information will justify in an operational (field) situation. The fourth prediction method, based on the use of idealized fallout patterns, is described in some detail below.

IDEALIZED FALLOUT PATTERNS

Megaton-Range Explosions

9.64 Idealized fallout patterns have been developed which represent the average fallout field for a given yield and wind condition. No attempt is made to indicate irregularities which will undoubtedly occur in a real fallout pattern, because the conditions determining such irregularities are highly variable and uncertain. Nevertheless, in spite of their limitations, idealized patterns are useful for planning purposes, for example in estimating the overall effect of fallout from a large-scale nuclear attack. Although they will undoubtedly underestimate the fallout in some locations and overestimate it in others, the evaluation of the gross fallout problem over the whole area affected should not be greatly in error.

9.65 For a detailed fallout prediction, the winds from the surface to all levels in the radioactive cloud must be considered. However, for the idealized patterns, the actual complex wind system is replaced by an approximately equivalent "effective wind." This is taken as the mean value of the wind speed and direction from the surface to some representative level in the cloud. The level chosen generally lies between the base and middle of the mushroom head, where the concentration of radioactivity is believed to be a maximum.

9.66 By assuming little or no wind shear, that is, essentially no change in wind direction at different altitudes, the idealized fallout patterns have a regular cigar-like shape, as will be seen shortly. But if the wind direction changes with altitude, the fallout will spread over a wider angle, as in Fig. 9.58a, and the activity (or radiation dose rate) at a given distance from surface zero will be decreased because the same amount of radioactive contamination will cover a larger area. Lower wind speeds will make the pattern shorter in the downwind direction because the particles will not travel so far before descending to earth; the activity at some distance from the burst point will be lower and the high dose rates immediately downwind of ground zero will be increased. If the wind speed is higher, the contaminated area will be greater, and the radioactivity will be higher at large distances from surface zero and lower immediately downwind of ground zero.

9.67 Before showing an idealized fallout pattern it is important to understand how such a pattern develops over a large area during a period of several hours following a 1-megaton fission yield surface burst. This may be illustrated by the diagrams in Figs. 9.67 a and b. The effective wind speed was taken as 15 miles per hour. Fig. 9.67a shows a number of "contours" (or "isodose-rate" lines) for certain (arbitrary) round-number values of the dose rate, as would be observed on the ground, at 1, 6, and 18 hours, respectively, after the explosion. A series of total (or accumulated) dose contours (or "isodose" lines) for the same times are given in Fig. 9.67b. It will be understood, of course, that the various dose rates and doses change gradually from one contour line to the next. Similarly, the last contour line shown does not represent the limit of the contamination, since the dose rate (and dose) will continue to fall off over a greater distance.

9.68 Consider, first, a location 22 miles downwind from ground zero. At 1 hour after the detonation, the observed dose rate is seen to be about 10 roentgens per hour but is rising very rapidly and will reach a value over 1,000 r/hr sometime between 1 and 2 hours and will

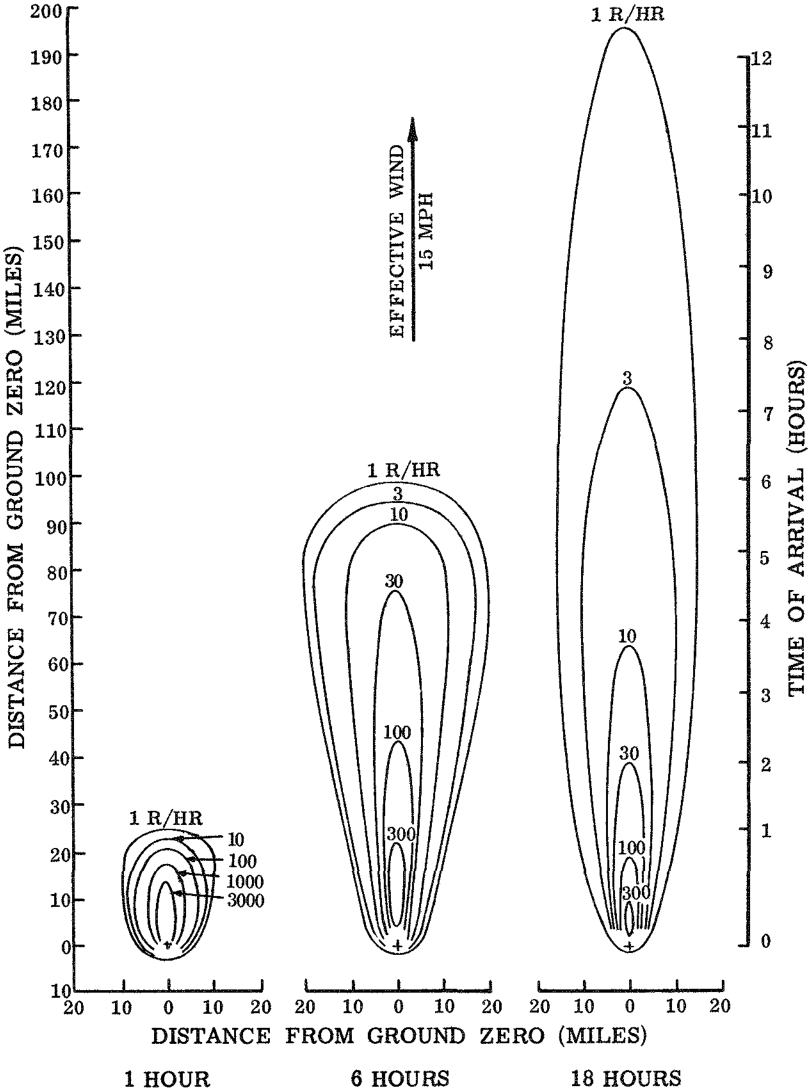

Figure 9.67a. Dose-rate contours from early fallout at 1, 6, and 18 hours after a surface burst with 1-megaton fission yield (15 mph effective wind speed).

then decay to about 300 r/hr at 6 hours. At 18 hours it is down to roughly 80 roentgens per hour. The increase in dose rate from 1 to 6 hours means that at the specified location the fallout was not complete at 1 hour after the detonation. The decrease from 6 to 18 hours

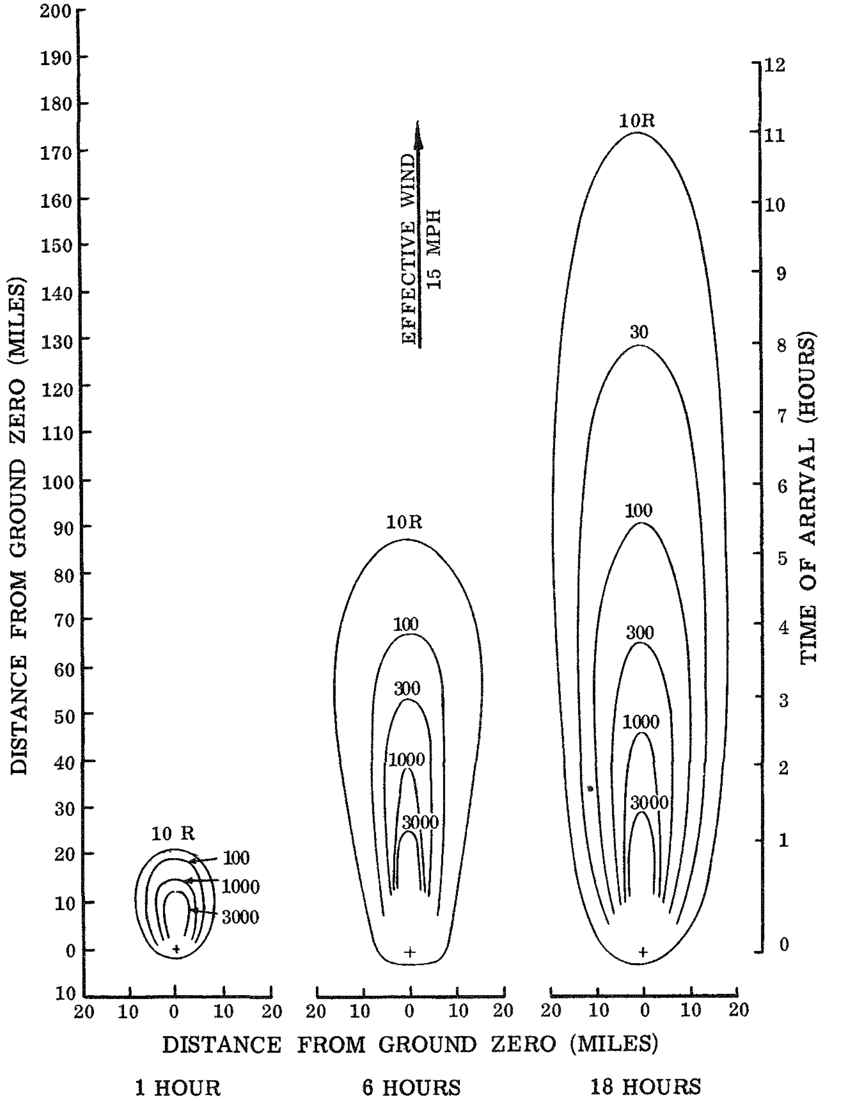

Figure 9.67b. Total-dose contours from early fallout at 1, 6, and 18 hours after surface burst with 1-megaton fission yield (15 mph effective wind speed).

is then due to the natural decay of the fission products. Turning to Fig. 9.67b, it is seen that the total radiation dose received at the given location by 1 hour after the explosion is small, because the fallout has only just started to arrive. By 6 hours, the total dose has

reached over 3,000 roentgens and by 18 hours a total dose of some 4,800 roentgens will have been accumulated. Subsequently, the total dose will continue to increase, toward the infinity value, but at a slower rate (§ 9.22).

9.69 Next, consider a point 100 miles downwind from ground zero. At 1 hour after the explosion the dose rate, as indicated in Fig. 9.67a, is zero, since the fallout will not have reached the specified location. At 6 hours, the dose rate is about 1 roentgen per hour and at 18 hours about 5 roentgens per hour. The fallout commences at somewhat less than 6 hours after the detonation and it is essentially complete at 9 hours, although this cannot be determined directly from the contours given. The total accumulated dose, from Fig. 9.67b, is seen to be zero at 1 hour after the explosion, less than 1 roentgen at 6 hours, and about 80 roentgens at 18 hours. The total (infinity) dose will not be as great as at locations closer to ground zero, because the quantity of fission products reaching the ground decreases at increasing distances from the explosion.

9.70 In general, therefore, at any given location, at a distance from a surface burst, some time will elapse between the explosion and the arrival of the fallout. This time will depend on the distance from ground zero and the effective wind velocity. When the fallout first arrives, the dose rate is small, but it increases as more and more fallout descends. After the fallout is complete, the radioactive decay of the fission products will produce a steady decrease in the dose rate. Until the fallout commences, the total dose will, of course, be zero, but after its arrival the total (accumulated) radiation dose will increase continuously, at first rapidly and then somewhat more slowly, over a long period of time, extending for many months and even years.

9.71 The curves in Figs. 9.71 a and b illustrate this behavior; they show the variation with time of the dose rate and the dose from fallout at points 35 and 150 miles downwind from a 5-megaton surface burst. Both the dose rate and the accumulated dose are zero until the fallout particles reach the given locations at 1 and 10 hours after the burst, respectively. At these times the dose rate commences to increase, reaches a maximum, and subsequently decreases, rapidly at first as the radioisotopes of short half-life decay, and then more slowly. The total dose increases continuously from the time of arrival of the fallout toward the limiting (infinite time) value.

9.72 The representation of dose rate and accumulated dose curves, of the form of Figs. 9.67 a and b, for all times following a nuclear detonation would obviously be a highly complicated matter. Fortunately, the situation can be simplified by utilizing an idealized

fallout pattern in terms of the unit-time reference dose rate, mentioned in §9.16 *et seq.* By means of the curves given earlier in the chapter (Figs. 9.16 a and b and Fig. 9.20) it is then possible to estimate dose rates and total doses from fallout at any given time for a specified distance downwind from the burst point. The calculations are valid only if all the early fallout has descended at that time.

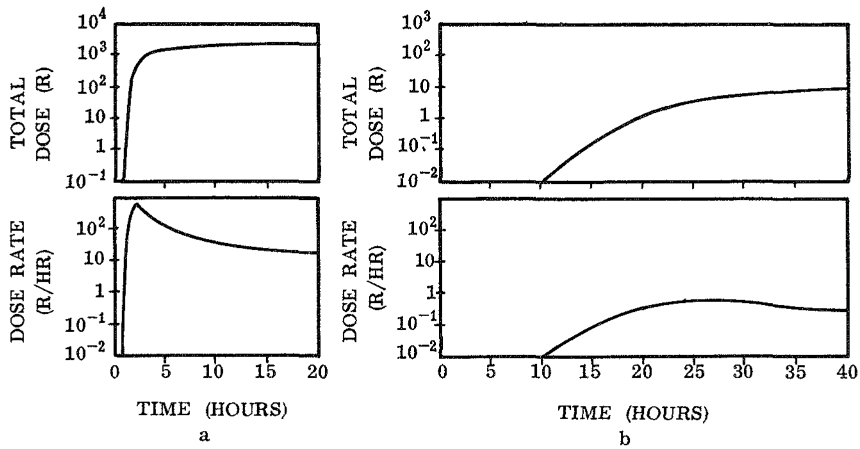

Figure 9.71a. Dose rate and accumulated dose from fallout as functions of time after the explosion at 35 miles downwind.

Figure 9.71b. Dose rate and accumulated dose from fallout as functions of time after the explosion at 150 miles downwind.

9.73 The idealized unit-time reference dose-rate contours for a 1-megaton fission yield surface burst, with an effective wind of 15 miles per hour, are represented in Fig. 9.73. This figure is based partly on observations made at various tests and partly on calculations. The maximum downwind distances and widths of the contours for various dose rates, down to 0.1 roentgen per hour, are recorded in Table 9.73. An example illustrating the use of Fig. 9.73 is given on the page facing the figure. No attempt is made here to express the upwind fallout pattern; this aspect of the problem will be considered later (§ 9.83).

9.74 It should be understood that the idealized dose rates and total dose calculations made from Fig. 9.73 would be those indicated by monitor instruments in open country in the complete absence of shielding from the residual nuclear radiations. Any kind of shelter would decrease the dose received from the early fallout.

Fallout Example

Given: A 10-megaton surface burst, with an effective wind speed from the surface to 80,000 feet of 25 miles per hour. Assume a fission yield of 50 percent.

Find: The unit-time reference dose rate, arrival time, and the dose received by an exposed person during the first week following fallout arrival at points 100, 200, and 300 miles downwind, and the upwind extent of the 1 r/hr unit-time reference dose rate.

Scaling procedures are described in § 9.75 *et seq.*; for upwind fallout distribution, see § 9.83 *et seq.* The scaling of the contours in Fig. 9.73 is explained in § 9.79.

Solution: The unit-time reference dose rates, scaled for wind speed, are found by plotting the scaled dose rates versus the scaled downwind distances, obtained from Fig. 9.73, to be 270 r/hr at 100 miles, 60 r/hr at 200 miles, and 24 r/hr at 300 miles. Scaling for the 5-megaton fission yield gives scaled unit-time dose rates of $5 \times 270 = 1{,}350$ r/hr, $5 \times 60 = 300$ r/hr, and $5 \times 24 = 120$ r/hr, respectively.

The cloud will be carried by the 25 mph wind to the 100 mile point in $100/25 = 4$ hours, to the 200 mile point in $200/25 = 8$ hours, and to the 300 mile point in $300/25 = 12$ hours.

In order to calculate the dose, an effective entry time equal to the arrival time may be assumed, giving effective entry times of 4, 8, and 12 hours for the 100, 200, and 300 mile points, respectively. Using Fig. 9.26, the total exposure doses for the first week are found to be about $1{,}350 \times 2 = 2{,}700$ r, $300 \times 1.50 = 405$ r, and $120 \times 1.2 = 144$ r, respectively.

From Fig. 9.85, the radius of the 1 r/hr contour for a 10-MT, 50-percent fission, burst is seen to be 21 miles. Because of the 25-mph wind, the downwind displacement of the center of the contours is $0.4 \times 25 = 10$ miles. Hence, the upwind extent of the 1 r/hr unit-time reference dose rate is $21 - 10 = 11$ miles.

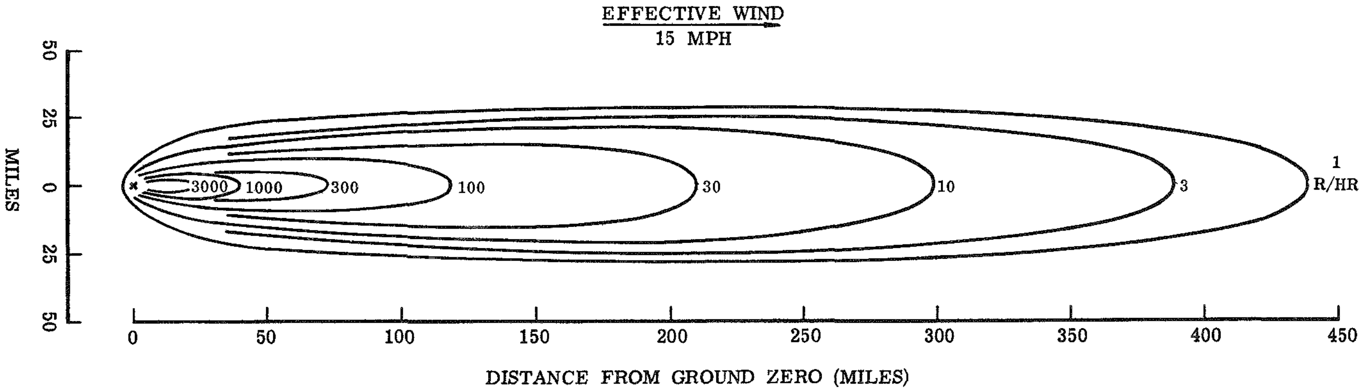

Figure 9.73. Idealized unit-time reference dose-rate pattern for early fallout from a 1-megaton fission yield surface burst (15 mph effective wind speed).

Table 9.73

DOWNWIND EXTENT OF UNIT-TIME REFERENCE DOSE-RATE CONTOURS FOR 1-MEGATON FISSION SURFACE BURST WITH 15 MPH WIND

Reference dose rate (roentgens/hour)	*Downwind distance (statute miles)*	*Maximum width (statute miles)*
3, 000	23	6
1, 000	42	10
300	74	12
100	120	18
30	210	30
10	300	42
3	390	50
1	440	56
0. 3	500	60
0. 1	530	62

Scaling

9.75 In order to obtain the idealized fallout pattern for a fission yield of F megatons, the values of the various contour lines in Fig. 9.73 may be multiplied by F. Thus, for a weapon having a total yield of M megatons with 50 percent of the energy derived from fission the factor would be 0.5 M. This scaling procedure, although highly simplified, gives reasonably good results for surface bursts from about 100 kilotons to 10 megatons fission yield. However, the higher values of dose rate (and dose) are probably overestimated for fission yields in excess of 1 megaton. Except for isolated points in the immediate vicinity of ground zero, observations indicate that unit-time reference dose rates greater than about 10,000 roentgens per hour are unlikely. A possible reason is that as the weapon yield increases so also does the initial volume of the radioactive cloud; hence, the maximum concentration of activity in the cloud does not change very much with the yield. The fallout contamination moderately near ground zero, where the dose rate is high, will thus not increase in proportion to the yield, as the simple scaling law given here implies. At greater distances downwind the law is much more reliable because, as a result of spreading by the wind, the initial cloud volume has relatively little influence on the concentration of fallout on the ground.

9.76 It should be noted that the proportional scaling procedure makes no allowance for the effect of the total, i.e., fission plus fusion, yield; thus it predicts the same fallout pattern for a 1-megaton all-

fission detonation as for a 2-megaton 50-percent fission explosion. Actually, the unit-time reference dose rate near ground zero might be somewhat smaller in the latter case because the same amount of radioactivity would be spread through a larger volume of the initial cloud. At greater distances downwind from the burst point the effect of the initial cloud concentration is small, as indicated above. Furthermore, at such locations the dilution effect may be compensated by the fact that the cloud from the 2-megaton explosion will probably rise higher, thus increasing the distances at which particles from the same relative position in the cloud will reach the ground.

9.77 As stated in § 9.65, the effective wind speed and direction are the mean values from the ground up to a certain level in the radioactive cloud, depending on the total yield of the explosion. As a very rough approximation, the atmospheric layers over which the wind is to be averaged as a function of the weapon yield, are as follows:

Total yield	*Layer*
Less than 1 MT	Surface to 40,000 feet.
1 MT to 5 MT	Surface to 60,000 feet.
More than 5 MT	Surface to 80,000 feet.

These values should be adequate for the rough evaluation of hypothetical fallout situations based on the idealized patterns. More elaborate prediction schemes take into consideration the winds at different levels instead of a single average effective wind.

9.78 If there is no directional wind shear, then doubling the wind speed would cause the particles of a given size to reach the ground at twice the distance from ground zero, so that they are spread over roughly twice the area. Based on this conclusion, the following scaling laws may be used in connection with the idealized fallout pattern: (*a*) the unit-time reference dose-rate value for each contour in the 15-mile-per-hour wind velocity pattern in Fig. 9.73 is multiplied by $15/v$, where v is the actual effective wind velocity in miles per hour and (*b*) the downwind distances in Fig. 9.73 are multiplied by $v/15$. For a 30-mile-per-hour wind, for example, the contour values would be halved and the distances doubled.

9.79 It will be apparent that in scaling for either yield or wind speed the values of the dose-rate contours are changed. The scaled downwind extent for any given contour value may readily be obtained by plotting the scaled dose rates versus the scaled downwind distances on logarithmic graph paper and reading downwind distances corresponding to the desired contour value from the resulting smooth curve.

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9.80 Both the idealized 15-mile-per-hour pattern in Fig. 9.73 and the wind scaling procedure tend to maximize the downwind extent of the dose-rate contours since they involve the postulate that there is very little (or no) wind shear. This is not an unreasonable assumption for the continental United States, since the wind shear is generally small at altitudes of interest from the standpoint of fallout. If there is considerable wind shear, e.g., 20° or more in the lower half of the mushroom head, the fallout pattern would be wider and shorter than that based on Fig. 9.73. The actual unit-time reference dose rate at a specified downwind distance from ground zero for a given effective wind speed would then be smaller than predicted. The crosswind values at certain distances might, however, be increased.

9.81 It may be noted that the method for wind scaling described in § 9.78 may be approximated by another procedure; the reference dose-rate contour values are left unchanged but the distances in Fig. 9.73 are multiplied by $(v/15)^{1/2}$. If considerable wind shear exists, a better approximation may be obtained by using the factor $(v/15)^{1/3}$. The results of this approximation are not reliable for dose rates greater than about 1,000 roentgens per hour for reasons similar to those given in § 9.75.

9.82 In order to emphasize the limitations of the idealized fallout patterns, Figs. 9.82 a and b are presented here. Figure 9.82a shows the idealized unit-time reference dose-rate contours for an 8-megaton, 50-percent fission surface burst and an effective wind speed of 40 miles per hour. Near ground zero the wind is from the southwest but the mean wind gradually changes to a westerly and then a northwesterly direction over a distance of a few hundred miles. In Fig. 9.82b an attempt is made to indicate what the actual situation might be like as a result of variations in local meteorological and surface conditions. The total contamination of the area is the same in both cases, but the details of the distribution, e.g., the occurrence of hot spots, which are shown shaded in Fig. 9.82b, is quite different. The pattern in Fig. 9.82b is hypothetical and not based on actual observations; its purpose is to call attention to the defects of the idealized fallout pattern. But since the factors causing deviations from the ideal vary from place to place and even from day to day, it is impossible to know them in advance. Consequently, the best that can be done here is to give an idealized pattern and show how it may be used to provide an overall picture of the contamination while, at the same time, indicating that in an actual situation there may be marked differences in the details of the distribution.

Upwind Fallout from Megaton-Range Explosions

9.83 A technique for predicting the ideal fallout contours in the upwind and crosswind directions has been developed from data obtained in connection with tests of devices in the megaton-energy range at the Eniwetok Proving Grounds. The treatment is based on the

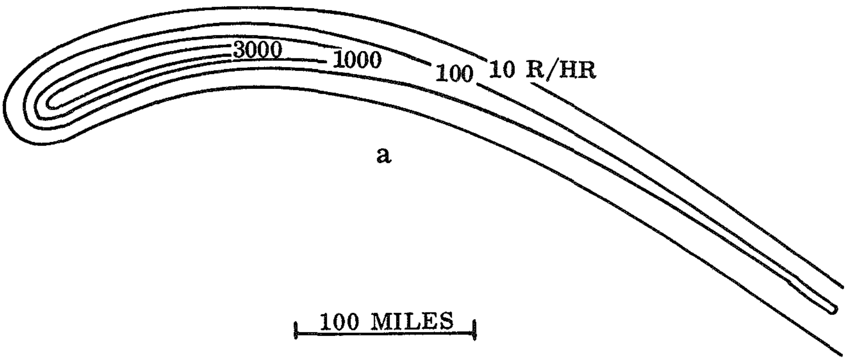

Figure 9.82a. Idealized unit-time reference dose-rate contours for an 8-megaton, 50-percent fission, surface burst (40 mph effective wind speed).

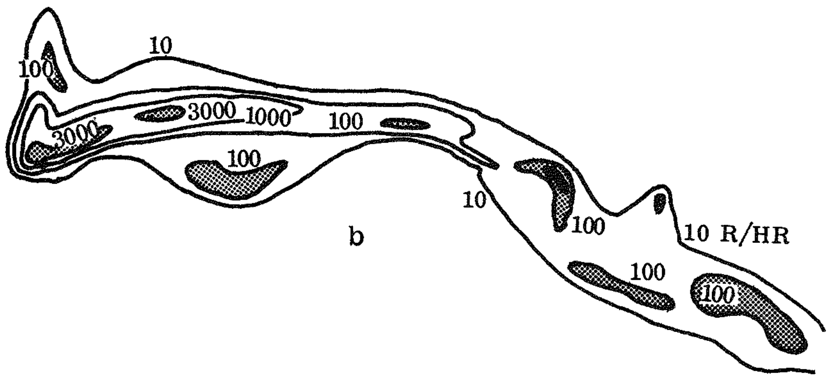

Figure 9.82b. Corresponding actual dose-rate contours (hypothetical).

expectation that the upwind extent of fallout will depend primarily on three factors: the maximum upwind extent of the radioactive cloud, the minimum time required for particles from the upwind edge of the cloud to reach the ground, and the mean effective wind from the ground to the altitude of the broadest part of the cloud.

9.84 Observations at Eniwetok have indicated that, for megaton-range detonations, the broad base of the cloud is generally stabilized

at almost the altitude of the tropopause, which is about 55,000 feet in the test area. The mean arrival time on the ground for upwind fallout was found to be about 30 minutes (0.5 hour). In the continental United States, the height of the tropopause is less and the estimated time of arrival is roughly 24 minutes (0.4 hour). Hence, while falling, particles from the upwind edge of the cloud would be carried downwind, i.e., back toward ground zero, a distance (in miles) equal to 0.5 times the mean effective wind speed (in miles per hour) at the Eniwetok Proving Grounds or 0.4 times the wind speed in the United States. The same reasoning may be applied to specific dose-rate contours. It may be assumed that if there were no wind, all the contours would be circles centered at ground zero. The radius of each contour would be determined only by the total yield and the fission percentage. Presumably, the radius of a contour would not be appreciably affected by the wind, but the center of the circles would be displaced in the downwind direction by the same distance the particles are carried downwind from the edge of the cloud.

9.85 From the available data on upwind and crosswind fallout in tests made at Eniwetok, contours for unit-time reference dose rates of 1, 10, and 100 roentgens/hour have been derived. These have been adjusted to zero wind speed and the radii of the corresponding circles are shown in Fig. 9.85 as a function of the total yield of the surface burst, assuming 50 percent fission. If the fission percentage is different from this value, then the indicated dose rates in Fig. 9.85 should be multiplied by the ratio of the actual fission percentage to 50 percent. The figure also gives the radius for a peak blast overpressure of 7 pounds per square inch, representing the area of almost total destruction, and the dimensions of the visible cloud at 10 minutes after the explosion, this being the average time at which the cloud becomes stabilized (§ 2.15).

9.86 To convert these results into the idealized contours for an actual situation, it is necessary to know the effective wind speed and direction. In view of the uncertainty of the height of the cloud base, it is recommended that the speeds for altitudes of both 40,000 and 60,000 feet be considered and the smaller one be taken for the present purpose. The wind direction, however, would be that for 40,000 feet.[4] Multiplication of the mean wind speed by 0.4 would then give the displacement from ground zero of the centers of the circular contours in the downwind direction in the United States.

[4] Mean wind speeds and expected direction of fall of particles, for various elevations, can be obtained from the "UF" (Upper-air Fallout) wind data reported regularly by the U.S. Weather Bureau.

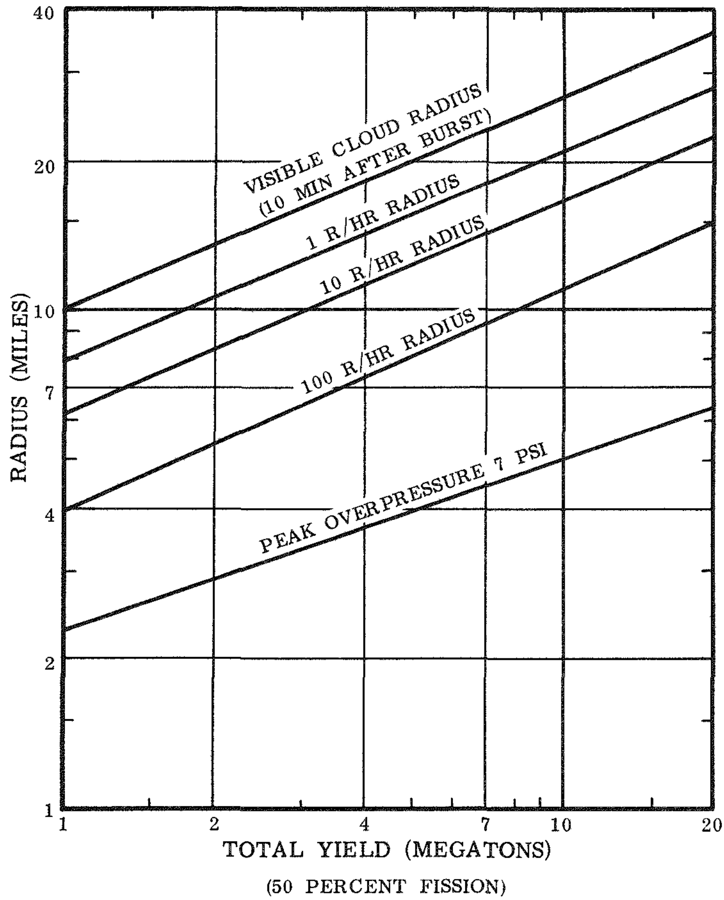

Figure 9.85. Radii for unit-time dose rates from early fallout, stabilized cloud, and 7-psi overpressure as function of total yield (50 percent fission) for surface bursts.

9.87 For purposes of illustration, consider a 10-megaton surface burst, with a 50-percent fission yield. Suppose that the mean wind from the surface to 40,000 feet is 25 miles per hour and its (downwind) direction is 30° east of north, and that the mean wind speed to 60,000 feet is 20 miles per hour. Hence, the effective wind to be used in constructing the upwind pattern is 20 miles per hour, but the direction is to be taken at 30° east of north. The displacement of the center of the contour circles is thus $0.4 \times 20 = 8$ miles, in the downwind direction.

From Fig. 9.85, the radii of the unit-time reference dose-rate contours for a 10-megaton burst are as follows:

1 roentgen/hour: 21 miles
10 roentgens/hour: 16.5 miles
100 roentgens/hour: 11 miles

Semicircles are now drawn having these radii with the point 8 miles downwind from ground zero as the center to give the actual upwind and crosswind contours, as shown in Fig. 9.87. Any contour, e.g., the one for 100 roentgens/hour, passing through the circle of severe blast damage (7 pounds per square inch overpressure), which has a radius of about 5 miles in the present case, may be regarded as uncertain. The area within the blast damage circle may be expected to be heavily contaminated by induced activity, stem fallout, and throwout, regardless of the wind speed.

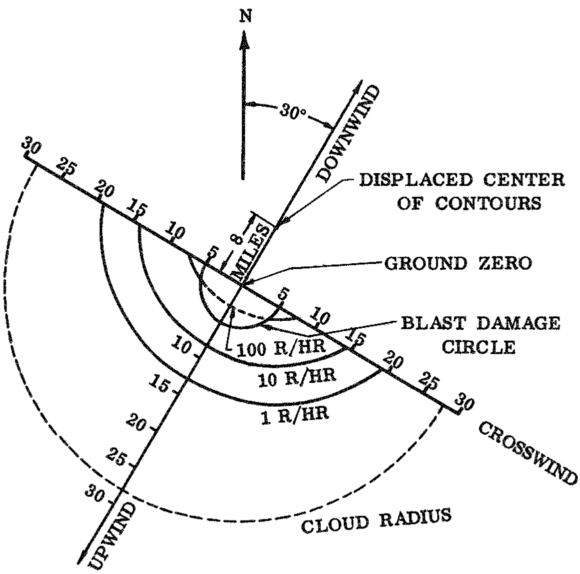

Figure 9.87. Illustration of calculation of upwind early fallout pattern.

9.88 The procedure described above is based on a number of assumptions, as are essentially all methods of fallout prediction. Nevertheless, it is felt that its shortcomings are outweighed by its simplicity and the fact that it can be used to provide a rapid, if approximate, estimate of the fallout contamination pattern in the upwind semicircle about ground zero.

KILOTON-RANGE EXPLOSIONS

9.89 The basic fallout phenomena associated with a surface burst in the kiloton-energy range are essentially the same as for detonations of higher yield. The proportionately smaller quantity of fission products will, of course, mean that smaller areas are contaminated to a serious extent. Furthermore, the lower cloud height will result in fallout coming to earth sooner and at closer distances to the burst point. However, the peak dose rate at ground zero and for a short distance downwind may well be of the same order of magnitude as for explosions in the megaton range.

9.90 Representative dose-rate contour dimensions for a 20-kiloton surface burst, with a mean wind velocity of 15 miles per hour, and little wind shear, are recorded in Table 9.90. The downwind extent of a given contour may be scaled for yields from about 1 to 100 kilotons and for any effective wind speed in the same manner as described above for 1-megaton fission yield contours. However, the prediction method for upwind fallout from megaton-range detonations is not applicable to the kiloton-energy range. The upwind fallout associated with these lower yields will be much less extensive because of the smaller cloud radius, e.g., 3 miles or less. Dose rates in the region around ground zero will still be very high because of induced activity, stem fallout, throwout from the crater, and the fallout of larger particles from the cloud.

TABLE 9.90

DOWNWIND EXTENT OF UNIT-TIME REFERENCE DOSE-RATE CONTOURS FOR 20-KILOTON SURFACE BURST WITH 15 MPH WIND

Reference dose rate (roentgens/hour)	*Downwind distance (statute miles)*	*Maximum width (statute miles)*
3, 000	1	<0.5
1, 000	3	<1.0
300	7	1
100	14	2
30	32	4
10	60	6
3	100	11
1	150	16

9.91 On the average, fallout patterns from kiloton-range detonations will be more affected by wind shear than for megaton explosions because the particles spend a larger fraction of their fall times in the turbulent lower atmosphere. The effect of wind shear will be to reduce the areas enclosed by the high dose-rate contours, making

them shorter and wider. In addition, very large areas may be covered by contamination of a low order.

UNCERTAINTIES IN FALLOUT PREDICTIONS

9.92 Although the procedures described above for developing idealized fallout patterns under various conditions are probably as good as can be expected, it must be emphasized that they are intended only for overall planning. There are several factors which will affect the details of the distribution of the early fallout and also the rate of decrease of the radioactivity. Near ground zero, activity induced by neutrons in the soil will be significant, apart from that due to the fallout. However, the extent of the induced activity is difficult to estimate, since it will depend on the type of weapon, e.g., the actual amounts of fission and fusion energy, the height of burst, and the nature of the soil. The existence of unpredictable hot spots will also affect the local radiation intensity. These are dependent upon a variety of conditions not all of which are fully understood. There is a possibility that the formation of a hot spot some distance downwind from ground zero is characteristic of high-yield explosions (§ 9.59). The nature of the terrain may also influence the dose rate at a given location as a result of incidential shielding. The data in Fig. 9.73 are applicable to moderately flat, uninhabited areas, such as those in which weapons tests are carried out. In a city, buildings, trees etc., might well reduce the average radiation intensity above the ground to 70 or 75 percent of this open-terrain value.

9.93 The rate of decay of the early fallout radioactivity, and hence the total dose accumulated over a period of time, will be affected by weathering. Wind may transfer the fallout from one location to another, thus causing local variations. Rain, on the other hand, may wash the fallout into the soil and this will tend to decrease the dose rate at a level a few feet above the ground. The extent of this decrease will, of course, depend on the climatic and surface conditions, but it has been estimated that, in temperate regions, the weathering effect will probably be negligible during the first month after the explosion, but that over a period of years the fallout dose rate would decrease to about half that which would otherwise be expected. If rain should occur at the time of the detonation, the fallout pattern might be changed considerably, as will be seen in § 9.95 *et seq.*

9.94 In attempting to predict the time that must elapse, after a nuclear explosion, for the radiation dose rate to decrease to a level that will permit reentry of a city or the resumption of agricultural

operations, use may be made of the (continuous) decay curves in Figs. 9.16a and b or of equivalent data. However, it is inadvisable to depend entirely on these estimates because of the uncertainties mentioned above. Moreover, even if the decay curve could be relied upon completely, which is by no means certain, the actual composition of the fallout is known to vary with distance from ground zero (§ 9.08) and the decay rate will vary accordingly. At 3 months after a nuclear explosion, the radiation intensity will have fallen to about 0.01 percent, i.e., one ten-thousandth part, of its value at 1 hour, so that almost any contaminated area will be safe enough to enter for the purposes of taking a measurement with a dose-rate meter, provided there has been no additional contamination in the interim.

Rainout of Radioactive Debris

9.95 If the airborne debris from a nuclear explosion should encounter a region where precipitation is occuring, a large proportion of the radioactive particles may be brought to earth with the rain. It should be noted, however, that the tops of rain-bearing clouds are generally below the 20,000-foot level, whereas the bulk of the radioactivity for detonations in excess of about 5-kilotons energy yield very soon attains a greater altitude. Hence, early fallout particles from a high-yield surface burst will spend only a fraction of their fallout time in the rain layer and the total amount of early fallout should not be significantly affected by the precipitation. The distribution of the fallout will probably be more irregular than in the absence of rain, with heavy showers producing local hot spots scattered within the contaminated area. Fallout from the cloud stem in an explosion of high yield should not be greatly influenced by precipitation since the particles in the stem will fall to earth in a relatively short time, regardless of whether there is precipitation or not.

9.96 In the surface detonation of a low-yield nuclear weapon in a rainy situation, the whole of the radioactive cloud might be within the rain layer. This would probably result in deposition on the ground of very nearly 100 percent of the fission product activity within a few hours after the explosion. The fallout (or rainout) pattern might cover a smaller area and the peak dose rates would be higher than in the absence of rain, but the difference would probably be less than an order of magnitude.

9.97 The fallout situation following an air burst of low total yield would be greatly altered by precipitation. If there were no precipitation, then this type of burst would produce virtually no local fallout.

Detonation in heavy rain, however, could result in almost as much early fallout (or rainout) as for a surface burst of the same fission yield.

9.98 In a high-yield air burst, essentially all the radioactive debris would generally be carried above the rain-bearing layer and there would be little or no early fallout. An important exception could arise if the airborne debris were to encounter thunderstorms, since precipitation may then originate as high as 60,000 feet. Should such an encounter take place within a few hours after the burst, localized hot spots of very high intensity might develop due to rainout. Although radioactive decay, wind shear, and diffusion all tend to reduce the concentration of activity in the cloud, thunderstorm scavenging of the weapon residues could still conceivably produce serious contamination of the ground many hours after detonation and hundreds of miles downwind from the point at which the air burst occurred.

9.99 It must be admitted that much of what has been stated above concerning the possible effects of rain on fallout from both surface and air bursts is based largely on theoretical considerations. Nuclear test operations have been conducted in such a manner as to avoid the danger of rainout. The few recorded cases of rainout which have occurred have involved very low levels of contamination and the possibility of severe contamination under suitable conditions has not been verified.

The High-Yield Explosion of March 1, 1954

9.100 The foregoing discussion of the distribution of the early fallout may be supplemented by a description of the observations made of the contamination of the Marshall Islands area following the high-yield test explosion (BRAVO) at Bikini Atoll on March 1, 1954.[5] The total yield of this explosion was approximately 15-megatons TNT equivalent. The device was detonated on a coral reef and the resulting fallout, consisting of radioactive particles ranging from about one-thousandth to one-fiftieth of an inch in diameter, contaminated an elongated area extending over 330 (statute) miles downwind and varying in width to over 60 miles. In addition, there was a severely contaminated region upwind extending some 20 miles from the point of detonation. A total area of over 7,000 square miles was contaminated to such an extent that avoidance of death or radiation

[5] "The Effects of High-Yield Nuclear Explosions." A report by the U.S. Atomic Energy Commission, Government Printing Office, February 1955.

injury would have depended upon evacuation of the area or taking protective measures.

9.101 The BRAVO shot is of particular interest because the predicted fallout patterns for megaton-range explosions, such as those given in §9.67 and §9.73, are largely based on inferences drawn from measurements made after this detonation. The available data, for the estimated total doses received at various locations at 96 hours after the explosion, are shown by the points in Fig. 9.101. Through these points there have been drawn a series of contour lines which appear to be in reasonably good agreement with the data. However, other patterns are possible; one, for example, ascribes the large radiation doses on the northern islands of Rongelap Atoll to a hot spot and brings the 3,000-roentgen contour line in much closer to Bikini Atoll. Because of the absence of observations from large areas of ocean, the choice of the fallout pattern, such as the one in Fig. 9.101, is largely a matter of guesswork. Nevertheless, one fact is certain: there was appreciable radioactive contamination at distances downwind of 300 miles or more from the explosion.

9.102 It should be noted that the doses to which the contours in Fig. 9.101 refer are values calculated from instrument records. They represent the maximum possible exposure and would be received only by those individuals who remained in the open, with no protection against the radiation, for the whole time. Any kind of shelter, e.g., within a building, or evacuation of the area would have reduced the dose received. On the other hand, persons remaining in the area for a period longer than 96 hours after the explosion would have received larger doses of the residual radiation.

9.103 A radiation dose of 700 roentgens spread over a period of 96 hours would probably prove fatal in the great majority of cases. It would appear, therefore, that following the test explosion of March 1, 1954, there was sufficient radioactivity from the fallout in a downwind belt about 170 miles long and up to 35 miles wide to have seriously threatened the lives of nearly all persons who remained in the area for at least 96 hours following the detonation without taking protective measures of any kind. At distances of 300 miles or more downwind, the number of deaths due to short-term radiation effects would have been negligible, although there would probably have been many cases of sickness resulting in temporary incapacity.

9.104 The period of 96 hours after the explosion, for which Fig. 9.101 gives the accumulated radiation exposures, was chosen somewhat arbitrarily. It should be understood, however, as has been frequently stated earlier in this chapter, that the radiations from the

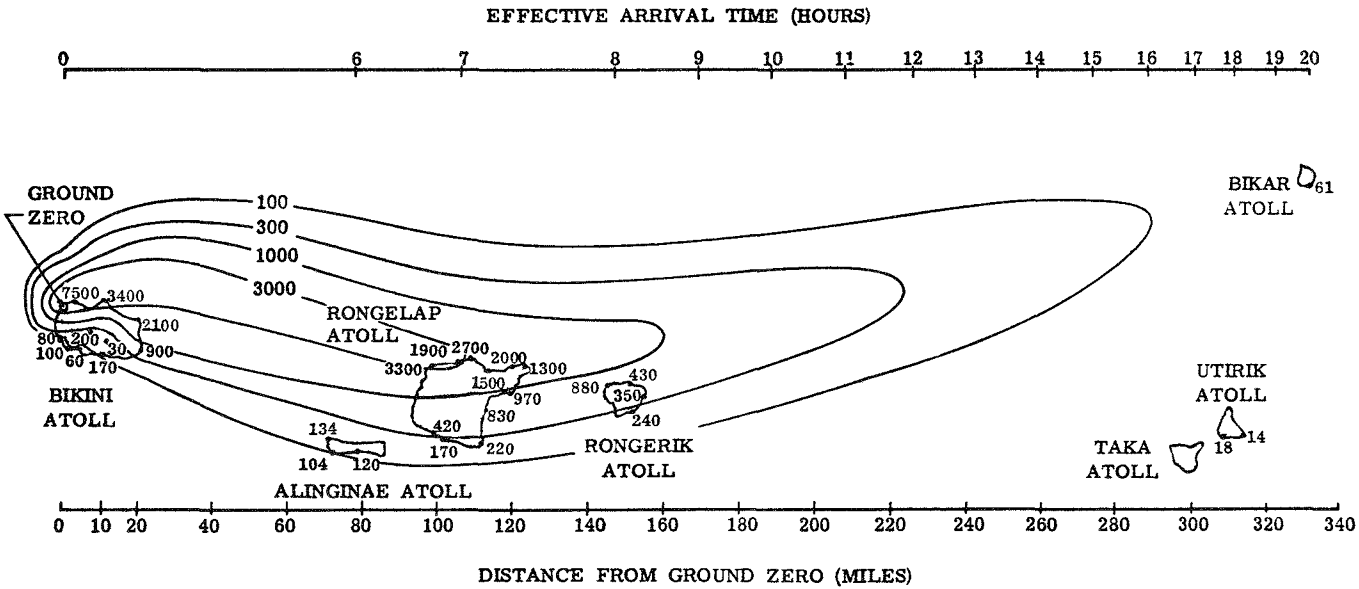

Figure 9.101. Estimated total-dose contours in roentgens at 96 hours after the BRAVO test explosion.

fallout will continue to be emitted for a long time, although at a gradually decreasing rate. The persistence of the external gamma radiation may be illustrated in connection with the BRAVO test by considering the situation at two different locations in Rongelap Atoll. Fallout began about 4 to 6 hours after the explosion and continued for several hours.

9.105 The northwestern tip of the atoll, 100 miles from the point of detonation, received 3,300 roentgens during the first 96 hours after the fallout started. This was the heaviest fallout recorded at the same distance from the explosion and may possibly have represented a hot spot, as mentioned above. About 25 miles south, and 115 miles from ground zero, the dose over the same period was only 220 roentgens. The inhabitants of Rongelap Atoll were in this area, and were exposed to radiation dosages up to 175 roentgens before they were evacuated some 44 hours after the fallout began (see § 11.126). The maximum theoretical exposures in these two areas of the atoll for various time intervals after the explosion, calculated from the decay curves given earlier in this chapter, are recorded in Table 9.105.

TABLE 9.105

CALCULATED RADIATION DOSES AT TWO LOCATIONS IN RONGELAP ATOLL FROM FALLOUT FOLLOWING THE MARCH 1, 1954 TEST AT BIKINI

	Accumulated dose in this period (roentgens)	
Exposure period after the explosion	*Inhabited location*	*Uninhabited location*
First 96 hours	220	3, 300
96 hours to 1 week	35	530
1 week to 1 month	75	1, 080
1 month to 1 year	75	1, 100
Total to 1 year	405	6, 010
1 year to infinity	About 8	About 115

9.106 It must be emphasized that the calculated values in Table 9.105 represent the maximum doses at the given locations, since they are based on the assumption that exposed persons remain out-of-doors for 24 hours each day and that no measures are taken to remove radioactive contamination. Furthermore, no allowance is made for weathering or the possible dispersal of the particles by winds. For example, the dose rates measured on parts of the Marshall Islands on the 25th day following the explosion were found to be about 40 percent of the expected values. Rains were known to have occurred during the second week, and these were probably responsible for the major decrease in the contamination.

9.107 In concluding the present discussion of fallout contamination, it may be noted that the 96-hour dose contours shown in Fig. 9.101, representing the fallout pattern in the vicinity of Bikini Atoll after the high-yield explosion of March 1, 1954, as well as the unit-time reference dose-rate contours in Fig. 9.73, can be regarded as more-or-less typical, so that they may be used for planning purposes. Nevertheless, it should be realized that they cannot be taken as an absolute guide. The particular situation which developed in the Marshall Islands was the result of a combination of circumstances involving the energy yield of the explosion, the height of burst, the nature of the surface below the point of burst, the wind system over a large area and to a great height, and other meteorological conditions. A change in any one of these factors could have affected considerably the details of the fallout pattern.

9.108 In other words, it should be understood that the fallout situation described above is one that *can* happen, but is not necessarily one that *will* happen, following the surface burst of a high fission-yield weapon. The general direction in which the fallout will move can be estimated fairly well if the wind pattern is known. However, the fission yield of the explosion and the height of burst, in the event of a nuclear attack, are unpredictable. Consequently, it is impossible to determine in advance how far the seriously contaminated area will extend, although the time at which the fallout will commence at any point could be calculated if the effective wind velocity and direction were known.

9.109 In spite of the uncertainties concerning the exact fallout pattern, there are highly important conclusions to be drawn from the results described above. One is that the residual nuclear radiation can, under some conditions, represent a serious hazard at great distances from a nuclear explosion, well beyond the range of blast, shock, thermal radiation, and the initial nuclear radiation. Another is that plans can be made to minimize the hazard, but such plans must be flexible, so that they can be adapted to the particular situation which develops after the attack.

RADIOACTIVE CONTAMINATION FROM NUCLEAR EXPLOSIONS

Radiological Warfare

9.110 For some time, consideration has been given to the possibility of using radioactive material deliberately as an offensive

weapon in what is called "radiological warfare." The basic idea is that radioactive contamination of areas, factories, or equipment would make their use either impossible or very hazardous without any accompanying material destruction. To be effective, a radiological warfare agent should emit gamma radiations and it should have a half-life of a few weeks or months. Radioisotopes of long half-life give off their radiations too slowly to be effective unless large quantities are used, and those of short half-life decay too rapidly to provide an extended hazard.

9.111 Even if a radioisotope with suitable properties and which could be readily manufactured were selected as a radiological warfare agent, the problems of production, handling, and delivery of the weapon emitting intense gamma radiation would not be easily solved. In addition, stockpiling the radioactive material would present a difficulty. Other weapons can be prepared in advance, ready for an emergency. They can be kept for a long time without suffering deterioration. This is not true for radiological warfare agents, for natural decay would result in a continuous loss of active material. The production of a specific radioisotope is a slow process, at best, and so the continual and unavoidable loss would be a serious drawback.

9.112 The situation has undergone a change with the development of weapons having high fission energy yields. The explosion of such devices at low altitudes can cause radioactive contamination over large areas that are beyond the range of physical damage. Consequently, they are, in effect, weapons of radiological warfare. Instead of preparing and stockpiling the contaminating agent in advance, with its attendant difficulties, the radioactive substances are produced by fission at the time of the explosion. Radiological warfare has thus become an automatic extension of the offensive use of nuclear weapons of high fission yield.

Contamination of Areas

9.113 It was suggested in § 9.110 that radioactive contamination could deny the use of considerable areas for an appreciable period of time. There are two aspects of this situation which merit consideration. First, the direct effect of the radiation exposure on human beings who might have to live or work in a contaminated region, and second, the indirect effect due to the consumption of food grown (and animals raised) in such an area. The methods for calculating exposure doses from fallout, assuming no protection, have been

given earlier in this chapter. The time that may be spent at a given location can thus be determined, provided some limit has been set concerning the total exposure dose. The value of such an emergency dose will vary, depending on the radiation history of the individual and the degree of hazard that he is willing to risk incurring under the existing conditions.

9.114 *In contaminated agricultural areas, the hazard to workers* could be reduced by turning over the earth, so as to bury the fallout particles. But there still remains the matter of absorption of radioisotopes from the soil by plants and their ultimate entry into the human system in food. It is known that some elements are taken up more easily than others, but the actual behavior depends on the nature of the soil and other factors. Some aspects of this subject are considered further in § 11.174 *et seq.*

Contamination in Subsurface Bursts

9.115 The extent of the contamination due to residual nuclear radiation following a subsurface explosion will depend primarily on the depth of the burst. If the explosion occurs at a sufficient depth below the surface, essentially none of the weapon residues and neutron-induced radioactive materials will escape into the atmosphere. There will then be no appreciable fallout. On the other hand, if the burst is near the surface, so that the fireball actually breaks through, the consequences, as regards fallout, will not be very greatly different from those following a surface burst.

9.116 There will, in fact, be a gradual transition in behavior from a high air burst, at one extreme, where all the radioactive residues are dissipated in the atmosphere, to a deep subsurface burst, at the other exteme, where the radioactive materials remain below the surface. In neither case will there be any significant local fallout. Between these two extremes are surface bursts or low air bursts which will be accompanied by extensive contamination due to early fallout. These merge into shallow subsurface bursts, for which the behavior is similar. With increasing depth of explosion, more of the radioactive residues remain in the vicinity of the burst point, i.e., in and around the crater, and proportionately less goes into the upper atmosphere to descend at a distance as fallout.

9.117 Since a shallow subsurface burst, in which the fireball emerges from the ground, is essentially similar to a surface burst, in which a large part of the fireball touches the earth, this type of nuclear explosion need not be discussed further. The case of in-

terest, however, is that of a subsurface burst at such a depth that the fireball does not emerge, yet a considerable amount of dirt (or water) is thrown up as a column into the air.

9.118 It may be noted that some contribution to the residual nuclear radiations following a subsurface detonation is made by the radioisotopes, e.g., sodium-24 (§ 9.35), formed by neutron capture. However, as with a surface burst, this is so small in comparison with the radiations from the fission products that it may be ignored.

9.119 In the case of an underground explosion at a moderate depth there will be considerable crater formation. Much of the radioactive material will remain in the crater area, partly because it does not escape and partly because the larger pieces of contaminated rock, soil, and debris thrown up into the air will descend in the vicinity of the explosion. The finer particles produced directly or in the form of a base surge (§ 2.89) will remain suspended in the air and will descend as a fallout at some distance from ground zero.

9.120 The early fallout contour pattern will be dependent upon the fission energy yield, the depth of burst, the nature of the soil, and also upon wind and weather conditions. Other circumstances being more or less equal, the contamination in the crater area following a subsurface burst will be about the same as for a surface explosion of equal fission yield. However, the total contaminated area will be greater for the shallow subsurface burst because a larger amount of fission products is present in the early fallout.

Underwater Explosions

9.121 In a shallow underwater explosion, radioactive contamination will arise from the visible and invisible base surge, which remains near the water surface, and from the radioactive, airborne cloud, which is produced by condensation of the vented weapon residues (Chapter II). The radioactive cloud does not ascend as high as it would for a surface (or low air) burst of the same yield and so a large proportion of the fission product activity rains out in a short time within a radius of a few thousand yards of surface zero. In the Bikini BAKER test (§ 2.61), the contaminated fallout (or rainout) consisted of both solid particles and of a slurry of salt crystals in drops of water. This contamination was difficult to dislodge and had there been personnel on board the ships used in the test, they would have been subjected to considerable doses of radiation if the fallout were not removed immediately.[6] Since the BAKER

[6] The technique of washdown of ships, by continuous flow of water over exposed surfaces to remove fallout as it settles, was developed as a result of the Bikini BAKER observations.

shot was fired in shallow water, the bottom material may have helped in the scavenging of the radioactive cloud, thus adding to the contamination. It is expected that for shallow bursts in very deep water the fallout from the cloud will be less than observed at the test in Bikini lagoon, and in some cases there may be no cloud at all.

9.122 The base surge, both visible and invisible, created by the water from the plume as it falls back on the surface, will carry radioactive particles outward rapidly, enveloping nearby ships and land stations. The dose rate of the "transient" radiation, i.e., radiation from a source which is moving past a given location, from the base surge can be very high, e.g., of the order of 100,000 roentgens per hour, at early times. However, the radiation intensity declines rapidly as the concentration of the activity decreases as a result of radial expansion of the base surge ring and decay of the fission products. The total radiation dose delivered at a given distance from surface zero will depend on the direction and velocity of the wind which carries the base surge with it; for ships close to the explosion, the dose can be lethal.

9.123 The relative contributions of the base surge and the fallout (and rainout) from the cloud will depend upon the distance from surface zero, the depth of burst, and the environment. It is possible that shots at slightly greater depths than Bikini BAKER may produce no radioactive cloud and then all the contamination will come from the base surge. The nearness of the bottom may have an important bearing upon whether a detonation at a certain depth will create an airborne cloud or not. Furthermore, atmospheric conditions may also affect the rainout. For these reasons, the BAKER shot may not necessarily be entirely typical of a shallow underwater burst.

9.124 For a deep underwater shot there will generally be no airborne cloud (§ 2.82) and consequently no fallout and rainout. The radiation hazard will then arise only from the base surge, the characteristics of which are similar to those for a shallow underwater detonation. Whether the base surge from a deeper shot will be more or less radioactive than from one at a shallower depth, will depend on the scavenging action of the water on the fission debris in the interior of the underwater steam bubble created by the explosion. If all the debris is injected into the base surge, it will be considerably more radioactive than from a shallow shot, when much of the fission product residues goes into the airborne cloud. On the other hand, if the detonation takes place at a sufficiently great depth, it is possible that most of the fission debris will remain in the water and little will go into the base surge. In any event, the exact behavior of the fission products is

believed to depend to a great extent on the precise condition of the bubble of gas and steam as it vents at the surface (§ 2.84).

9.125 There will always be some gaseous products of the fission process that are more or less insoluble in water. These radioactive gases may jet out of the plume and drift skyward, for shots fired at a moderate depth. Hence, even in the absence of a regular cloud, they will constitute a radioactive hazard in addition to the base surge.

9.126 The phenomena associated with nuclear explosions on the surface of the water will probably be similar to those at shallow depth; however, the probability of creating a base surge has not been established. The fallout and rainout from the cloud will also be subject to many variations dependent upon atmospheric conditions.

9.127 Most of the radioactivity remaining in the water and on the bottom after an underwater or water surface burst will be found initially in the vicinity of the shot. For detonations occurring in deep water, activity will be left behind at layers where the hot gas and steam bubble was in a contraction phase during the course of its rise through the water (§ 2.84). Fallback from the plume and venting of the bubble will leave considerable amounts of contamination on the surface near the burst point. This will rapidly diffuse downward and outward, thus reducing the activity level to safe limits for ships' personnel within 15 minutes to an hour.

9.128 An indication of the rate of spread of the active material and the decrease in the dose rate following a shallow underwater burst is provided by the data in Table 9.128, obtained after the Bikini BAKER test. Although the dose rate in the water was still fairly high after 4 hours, there would be considerable attenuation in the interior of a ship, so that during the time required to cross the contaminated area the total dose received would be small. Within 2 or 3 days after the BAKER test the radioactivity had spread over an area of about 50 square miles, but the radiation dose rate in the water was so low that the region could be traversed in safety.

9.129 The radioactivity falling back on the sea from the high airborne cloud will extend downwind much farther than the base surge or that transported by the water. However, it will be much less significant than other sources of contamination, the level of activity seldom being such as to prohibit operation of modern ships. The fallout debris quickly mixes with the water and since the water absorbs (or attenuates) the radiation to a considerable extent, the hazard is much less than would result from the same fallout on land. The radioactive water will gradually be transported to other locations by the prevailing currents, and if these are known, the path of the contaminated water can be predicted.

TABLE 9.128

DIMENSIONS AND DOSE RATE OF CONTAMINATED WATER AFTER THE 20-KILOTON UNDERWATER EXPLOSION AT BIKINI

Time after explosion (hours)	*Contaminated area (square miles)*	*Mean diameter (miles)*	*Maximum dose rate (roentgens per hour)*
4	16. 6	4. 6	3. 1
38	18. 4	4. 8	0. 42
62	48. 6	7. 9	0. 21
86	61. 8	8. 9	0. 042
100	70. 6	9. 5	0. 025
130	107	11. 7	0. 008
200	160	14. 3	0. 0004

ATTENUATION OF RESIDUAL NUCLEAR RADIATION

Alpha and Beta Particles

9.130 In their passage through matter, alpha particles produce considerable direct ionization and thereby rapidly lose their energy. After traveling a certain distance, called the "range," an alpha particle ceases to exist as such.[7] The range of an alpha particle depends upon its initial energy, but even those from plutonium, which have a fairly high energy, have an average range of only just over 1½ inches in air. In more dense media, such as water or body tissue, the range is less, being about a one-thousandth part of the range in air. Consequently, alpha particles from radioactive sources are unable to penetrate even the outer layer of the skin (epidermis). It is seen, therefore, that as far as alpha particles arising from sources outside the body are concerned, attenuation is no problem.

9.131 Beta particles, like alpha particles, are able to cause direct ionization in their passage through matter. But the beta particles dissipate their energy less rapidly and so have a greater range in air and in other materials. Many of the beta particles emitted by the fission products traverse a total distance of 10 feet (or more) in the air before they are absorbed. However, because the particles are continually deflected by electrons and nuclei of the medium, they follow a tortuous path, and so their effective (or net) range is somewhat less.

9.132 The range of a beta particle is shorter in more dense media, and the average net distance a particle of given energy can travel in

[7] An alpha particle is identical with a nucleus of the element helium (§ 1.62). When it has lost most of its (kinetic) energy, it captures two electrons and becomes a harmless (neutral) helium atom.

water, wood, or body tissue is roughly one-thousandth of that in air. Persons in the interior of a house would thus be protected from beta radiation arising from fission products on the outside. It appears that even moderate clothing provides substantial attenuation of beta radiation, the exact amount varying, for example, with the weight and number of layers. Only beta radiation from material ingested or in contact with the skin poses a hazard (§ 11.148).

Gamma Radiation

9.133 The residual gamma radiations present a different situation. These gamma rays, like those which form part of the initial nuclear radiation, can penetrate considerable distances through air and into the body. Shielding will be required in most fallout situations to reduce the radiation dose to an acceptable level. Incidentally, any method used to decrease the gamma radiation will also result in a much greater attenuation of both alpha and beta particles.

9.134 The absorption of the residual gamma radiation from fission products and from radioisotopes produced by neutron capture, e.g., in sodium, manganese, and in the weapon residues, is based upon exactly the same principles as were described in Chapter VIII in connection with the initial gamma radiation. Except for the earliest stages of decay, however, the gamma rays from fallout have much less energy, on the average, than do those emitted in the first minute after a nuclear explosion. This means that the residual gamma rays are more easily attenuated; in other words, compared with the initial gamma radiation, a smaller thickness of a given material will produce the same degree of attenuation.

9.135 Calculation of the attenuation of the gamma radiation from fallout is different and in some ways more complicated than for the initial radiations. The latter emanate from the explosion point, but the residual radiations arise from contamination which is widely distributed on the ground, on roofs, trees, etc. The complication stems from the fact that the effectiveness of a given thickness of material is influenced by the fallout distribution (or geometry) and hence depends on the degree of contamination and its location relative to the position where protection is desired. Estimates of the attenuation of residual radiation in typical residential structures have been made, based partly on calculations and partly on measurements with simulated fallout.

9.136 Some of the results obtained for various locations are given in Table 9.136 for one- and two-story, brick-veneer and wood-frame

houses, respectively. The "protection factor" is the ratio of the dose which would be received outdoors, without any protection, to that received at the indicated location in the structure. It should be emphasized that, while the values in the table are considered to be fairly representative, they must not be regarded as being exact. Deviations are to be expected because of differences in constructional details and environment, e.g., effect of nearby buildings.

TABLE 9.136

PROTECTION FACTORS AT VARIOUS LOCATIONS IN TYPICAL RESIDENTIAL STRUCTURES

	Type of structure			
	One-story brick veneer		One-story frame	
	Location			
First floor area (*sq ft*)	Center of ground floor	Center of basement	Center of ground floor	Center of basement
1,000	3.4	22	2.3	20
1,200	3.1	18	2.2	17
1,500	3.1	16	2.3	15
2,000	3.0	14	2.2	13
	Type of structure			
	Two-story brick veneer		Two-story frame	
	Location			
First floor area (*sq ft*)	Center of ground floor	Center of basement	Center of ground floor	Center of basement
1,000	4.4	54	2.3	44
1,200	4.4	41	2.4	37
1,500	4.4	37	2.4	34
2,000	4.1	34	2.4	29

9.137 The data in the table show that the heavier type of construction (brick veneer) provides better protection than a frame dwelling. It will be noted, too, that the protection factors in the middle of the ground floor of a wood-frame house are approximately the same for one- and two-story structures, but are appreciably different for brick-veneer houses. The reason is that in the latter case

the fallout on the roof contributes a larger fraction of the overall dose than for the lighter walled construction. Consequently, reducing the radiation from the roof by increasing the separation distance, in the two-story house, produces a greater change in the dose (and protection factor) in the case of the brick-veneer house. In each type of dwelling the protection factor expected at the center of the ground floor does not change very much as the floor area is increased. This is because there is a compensation between the increase in dose received from fallout on the roof and the decrease due to the greater distance from the outside.

9.138 The advantages of a basement location in providing protection against fallout radiation in any type of house are obvious from Table 9.136. The values given apply only if no part of the basement wall is exposed; in other words, it must be completely covered by earth and there must be no window openings. Under these circumstances, greater protection can be obtained near the exterior wall than in the center of the basement, because there is a decrease in the radiation from fallout on the roof. This is one reason why it is generally recommended that fallout shelters be constructed in the basement adjacent to an outer wall which is not exposed in any way (§12.55).

9.139 Typical protection factor ranges for a wide variety of structures of different types are summarized in Table 9.139. All the structures are assumed to be isolated, so that the effects, if any, of adjacent buildings have been neglected. From these values, rough estimates can be made of the shielding from fallout radiation that might be expected under various conditions.

9.140 It is of interest to mention that a simple one-man foxhole, 3 feet in diameter and 4 feet deep, can provide a protection factor of about 40 if fallout is present up to the edge, but not inside. If an area 3 or 4 feet wide around the foxhole is kept free of fallout material, a protection factor of 100 or more is possible.

DELAYED FALLOUT

Introduction

9.141 Before proceeding to a description of delayed fallout, a general comparison may be made between the two types of fallout. In addition to corresponding to different physical situations, with regard to space and time, the early and delayed fallout represent different biological hazards. The principal hazard from early fallout

TABLE 9.139

PROTECTION FACTOR RANGES FOR VARIOUS STRUCTURES

Type of structure	*Protection factor range*
Underground shelters (3 ft earth cover or equivalent). Sub-basements of multistory buildings.*	1,000 or greater
Basement fallout shelters (heavy masonry residences). Basements without exposed walls of multistory masonry buildings. Central areas of upper floors (excluding top 3 floors) of high-rise buildings † with heavy floors and exterior walls.	250 to 1,000
Basement fallout shelters (frame and brick veneer residences). Central areas of basements with partially exposed walls in multistory buildings. Central areas of upper floors (excluding top floor) of multistory buildings with heavy floors and exterior walls.	50 to 250
Basements without exposed walls of small 1- or 2-story buildings. Central areas of upper floors (excluding top floor) of multistory buildings with light floors and exterior walls.	10 to 50
Basements (partially exposed) of small 1- or 2-story buildings. Central areas on ground floor in 1- or 2-story buildings with heavy masonry walls.	2 to 10
Above ground areas of light residential structures.	2 or less

* Multistory buildings are those having from 3 to about 10 stories.
† High-rise buildings have more than about 10 stories.

arises from the possible exposure to gamma rays from sources outside the body, with the effect of beta particles from fallout material in direct contact with the skin as secondary. Because most of the radioisotopes in the early fallout have relatively short half-lives, the activity decays fairly rapidly and will have decreased by a factor of several thousand after 6 months (or less). The delayed fallout hazard, on the other hand, is due to radioactive material, particularly strontium-90, which is ingested as food. The strontium-90 accumulates in the bone and part may remain there for many years, representing a prolonged internal hazard. Both early and delayed fallout can have long-term genetic effects, but they are probably of less significance than other deleterious effects to be expected. These and related aspects of fallout are discussed more fully in Chapter XI.

9.142 The very fine particles present in the radioactive cloud, with radii of a few microns or less (§ 9.47), fall extremely slowly under the influence of gravity. Consequently, they remain suspended in the

atmosphere for a considerable time and may be carried over great distances as a result of the movements of the air. Ultimately, the radioactive particles are brought to the ground, primarily by the scavenging action of rainfall, and so produce the delayed fallout. Essentially all of the residual nuclear radiation from an air burst contributes to the delayed fallout, for in explosions of this type there is very little early (or local) fallout. For land surface bursts, about 40 percent of the residual activity appears as delayed fallout, whereas for surface bursts over water the proportion has been estimated to be about 70 percent (§ 9.48).

9.143 There are two respects, in particular, in which the delayed fallout is of special importance. First, many of the small contaminated particles will remain aloft for a long time—weeks, months, and sometimes years—so that the delayed fallout will be spread over large areas of the earth's surface. Second, although the radioisotopes of short life will have decayed almost completely before most of the delayed fallout reaches the ground (see, however, § 9.160, footnote), those having a long life will remain. Among these there are two, namely, strontium-90 (half-life 27.7 years) and cesium-137 (half-life 30.5 years), having great biological significance. Not only do these isotopes decay fairly slowly, but they both constitute relatively large fractions of the fission products; thus, for every 1,000 atoms undergoing fission there are eventually formed from 30 to 40 atoms of strontium-90 and from 50 to 60 of cesium-137. Moreover, both of these isotopes have gaseous precursors (or ancestors), so that, as a result of the process of fractionation (§ 9.08), their proportions in the delayed fallout will tend to be greater, at least for surface bursts, than in the fission products as a whole. Although the strontium and cesium in the delayed fallout make a negligible contribution to the external radiation dose, compared with that from the early fallout, their importance lies in the possibility that they may get into the body by way of food.

9.144 The ultimate distribution of the delayed fallout over the earth's surface is not affected by the particular wind conditions at the time of the detonation nearly as much as that of the early fallout. What is more important is the manner in which the contaminated particles enter the upper atmosphere. In order to understand the situation, it is necessary to review some of the characteristic features of the atmosphere.

Structure of the Atmosphere

9.145 One of the most significant aspects of the atmosphere is the variation in temperature at different altitudes and its dependence on latitude and time. In ascending into the lower atmosphere, from the surface of the earth, the temperature of the air falls steadily, in general, toward a minimum value. This region of falling temperature is called the "troposphere" and its top, where the temperature ceases to decrease, is known as the "tropopause." Above the troposphere is the "stratosphere," where the temperature remains more or less constant with increasing altitude in the temperate and polar zones. Although all the atmosphere immediately over the tropopause is commonly referred to as the stratosphere, there are areas in which the structure varies (Fig. 9.145). In the equatorial regions, the temperature in the stratosphere increases with height. This inversion also occurs at the higher altitudes in the temperate and polar regions. In the "mesosphere" the temperature falls off again with increasing height. At still higher altitudes is the "thermosphere" where the temperature rises rapidly with increasing height.

9.146 Most of the visible phenomena associated with weather occur in the troposphere. The high moisture content, the relatively high temperature at the earth's surface, and the convective movement (or instability) of the air arising from temperature differences promote the formation of clouds and rainfall. In the temperate latitudes, at about 45° in the summer and 30° in the winter, where the cold polar air meets the warm air of the tropics, there are formed meandering, wavelike bands of storm fronts called "polar fronts" (Fig. 9.145). In these regions, the average rainfall is high.

9.147 The tropopause, that is the top of the troposphere, is lower in the polar and temperate zones than in the tropics; its height in the former regions varies from 25,000 to 45,000 feet, depending on latitude, time of year, and particular conditions of the day. In general, the altitude is lowest in the polar regions. The tropopause may disappear entirely at times in the polar winter night. In the tropics, the tropopause usually occurs near 55,000 feet at all seasons. It is more sharply defined than in the temperate and polar regions because in the tropics the temperature increases with height above the tropopause instead of remaining constant. There is a marked gap or discontinuity in the tropopause in each temperate zone, as may be seen in Fig. 9.145, that constitutes a region of unusual turbulence. This gap moves north and south seasonally, following the sun, and is usually located near a polar front. It is believed that considerable

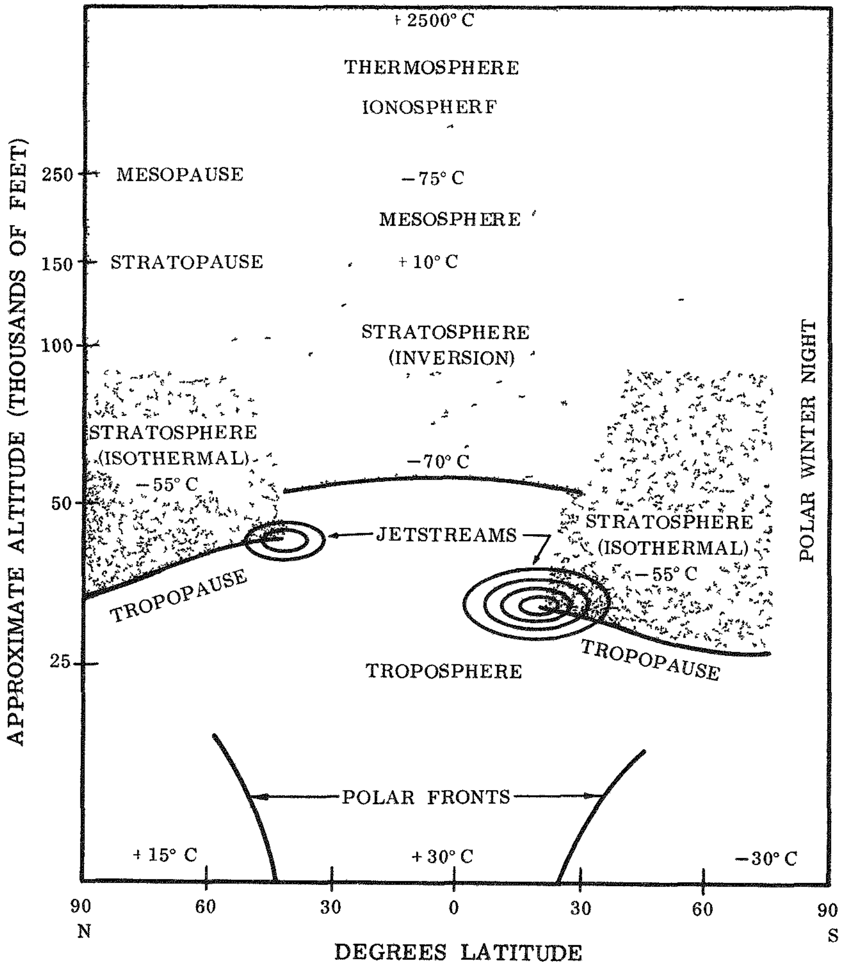

Figure 9 145 Structure of the atmosphere durmg Julv and August

interchange of air between the stratosphere and troposphere takes place at the gap A jet stream, forming a river of air moving with high speed and circulating about the earth, is located at the tropical edge of the polar tropopause in each hemisphere

9.148 Because of its temperature structure, there is very little convective motion in the stratosphere, and the air is exceptionally stable. This is especially noticeable in the tropics where the vertical movement of the radioactive cloud from a nuclear explosion has sometimes been less than 2 miles in three trips around the globe, i.e.,

approximately 70,000 miles. This stability continues up to the mesosphere where marked turbulence is again noted. The polar stratosphere is less stable than that in the tropics, particularly during the polar winter night when the stratospheric temperature structure changes to such an extent that the inversion may disappear. When this occurs there may be considerable convective mixing of the air to great heights.

Atmospheric Paths of Delayed Fallout: Tropospheric Fallout

9.149 The fallout pattern of the very small particles in the radioactive cloud which remain suspended in the atmosphere depends upon whether they were initially stabilized in the troposphere or in the stratosphere. The distribution of the radioactive material between the troposphere and the stratosphere depends mainly on the total energy yield of the explosion, the height of burst, the environment of the detonation, and the height of the tropopause. Additional complicating factors are scavenging by dirt or water and fractionation in surface bursts. Scavenging will tend to decrease the proportion of radioactive debris remaining in the cloud while increasing that in the early fallout, whereas fractionation will result in a relative increase in the amounts of strontium-90 and cesium-137 that remain suspended (§ 9.08). Consequently, it is difficult to predict the distribution between troposphere and stratosphere, but rough estimates have been made. Since strontium-90 is of particular interest in the delayed fallout, the calculated percentage of this isotope formed in a nuclear explosion that might enter the stratosphere under various conditions is shown in Fig. 9.149. The breadth of the bands is an indication of the uncertainty of the estimates.

9.150 In general, a larger proportion of strontium-90 will go into the stratosphere in an air burst than in a surface burst under the same conditions; for one thing, there is essentially no local or early fallout in the former case, and for another, surface material taken up into the cloud tends to depress the height attained in the latter case. In the temperate and polar regions, more strontium-90 enters the stratosphere from an air burst than for an equivalent burst in the tropics. The reason is that the tropopause is lower and the stratosphere is less stable in the non-tropic regions. For low-yield explosions, most of the radioactive material remains in the troposphere, with little entering the stratosphere. But since the altitude to which the cloud rises increases with the explosion energy yield, the proportion of strontium-90 passing into the stratosphere will increase correspondingly.

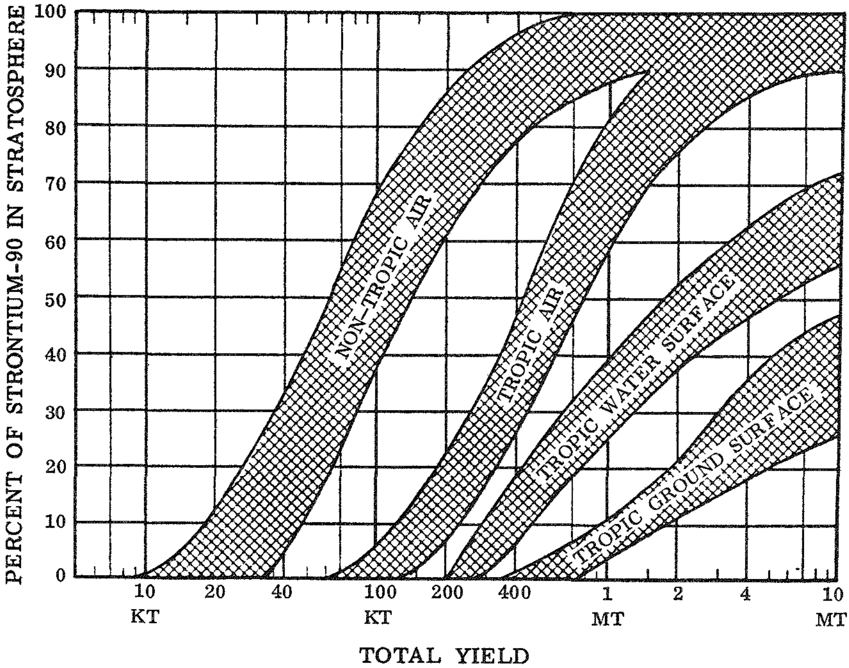

Figure 9.149. Theoretical percentage of strontium-90 injected into stratosphere as a function of total yield and burst conditions.

9.151 The small particles remaining in the troposphere descend to earth gradually over a period of time up to several months; this constitutes the "tropospheric fallout." The most important mechanism for causing this fallout appears to be the scavenging effect of rain and snow. The fine particles may be incorporated into the water droplets (or snow crystals) as they are formed and are thus brought down in the precipitation. Except for unusually dry or wet regions, the amount of delayed fallout deposited in adjacent areas is closely related to the amount of precipitation in those areas during the fallout period. Dry fallout has been recorded, but it probably represents a minor proportion of the tropospheric fallout in most instances.

9.152 The rate of removal of material from the troposphere at any time is roughly proportional to the amount still present at that time; consequently, the "half-residence time" concept is useful. It is defined as the period of time required at a given location for the removal of half the suspended material. If the cloud particles originally reached the upper part of the troposphere, the half-residence

time for tropospheric fallout is from 2 to 6 weeks. During the course of its residence in the atmosphere, the tropospheric debris is carried around the earth, by generally westerly winds, in perhaps a month's time. The bulk of the fallout on the average is then confined to a relatively narrow belt that spreads to a width of about 30° of latitude.

9.153 An idealized representation of the possible tropospheric fallout distribution from a detonation in the temperate zone is given in Fig. 9.153, in which the ordinates refer to the activity of isotopes having average lives of at least a month. One curve shows the variation of the relative activity of the deposited material with distance along the downwind fallout axis; it has a steep slope because the particles spread farther and farther from the axis, and so cover larger areas, as the distance from ground zero increases. If total activity were being considered, including that of isotopes of short life, the relative intensity would fall off even more sharply with distance because of the decay occurring before the particles descended to earth.

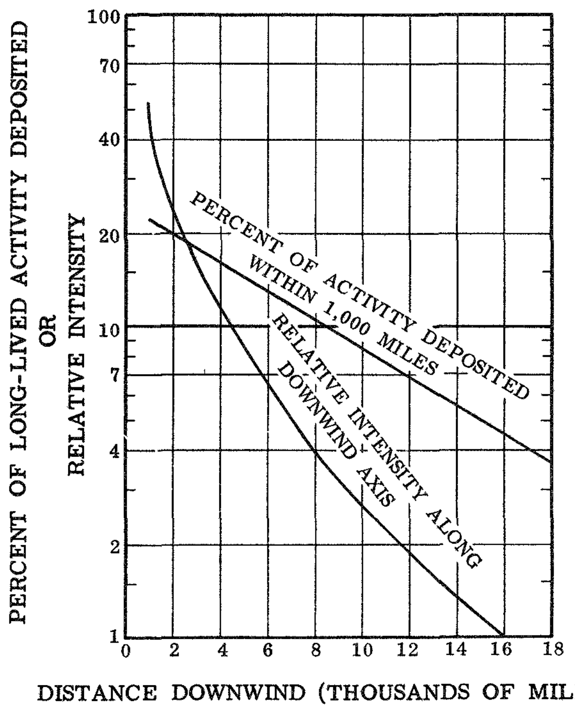

Figure 9.153. Percentage of long-lived activity deposited in troposphere and relative intensity downwind as function of distance.

The second curve indicates the percentage of the longer lived activity that might be deposited within 1,000 miles of locations on the downwind fallout axis. The idealized curves are based on the assumptions of uniform wind and moderate rainfall patterns in the downwind direction. However, the weather pattern existing during the first few weeks following a nuclear detonation can markedly change the picture represented in Fig. 9.153. Since uniform winds and rainfall are not very probable, the tropospheric fallout patterns, like those of the early fallout, will vary and may be quite irregular.

Stratospheric Fallout

9.154 The radioactive cloud debris that enters the stratosphere descends much more slowly than does the tropospheric fallout. This is mainly due to the fact that vertical motions in the stratosphere are slow, as stated above, and little moisture is available to scavenge the particles. It appears that almost the only way for the removal of the radioactivity from the stratosphere is for the air masses carrying the particles to move first into the troposphere, where the particles can be brought down by precipitation. There are at least three ways in which this transfer of air from the stratosphere to the troposphere can occur, they are (1) direct downward movement across the tropopause, (2) upward movement of the tropopause or its reformation at a higher altitude, and (3) turbulent, large-scale meandering horizontal circulation through the tropopause gaps. The relative importance of these mechanisms depends upon the altitude, latitude, and time of year at which the injection into the stratosphere takes place. The first method may be important during the arctic winter and the second in the lower polar stratosphere in the early spring. The third mechanism is particularly applicable to material in the lower stratosphere near the gaps. Very little debris crosses the tropopause in equatorial regions.

9.155 The winds in the stratosphere are predominantly easterly or westerly, depending on the place and time. Hence, when the radioactive cloud is injected into the stratosphere it tends to move in the downwind direction and ultimately becomes a streak girdling the globe more or less at the latitude of injection. This cloud gradually widens in a north-south direction and, very much more slowly, in a vertical direction by turbulent diffusion. A slow meridional circulation may cause a gradual shift of the cloud towards the polar region. The relatively complicated structure of the stratosphere and the varied modes by which contaminated particles may leave it, make it impos-

sible to assign a single half-residence time for stratospheric debris. In fact, there is some doubt whether the concept of half-residence time is strictly applicable. However, an effective half-residence time may be calculated from the time required for the removal of 80 percent of the material suspended in the stratosphere.[8]

9.156 The effective half-residence times obtained in this manner vary with both latitude and altitude of injection, but reasonable success in predicting stratospheric delayed fallout rates has resulted from assigning effective half-residence times of 5 months to debris entering the polar stratosphere (up to 70,000 feet), 10 months for the lower tropical stratosphere (up to 70,000 feet), 30 months for the higher stratosphere (70,000 to 110,000 feet), and 60 months for the highest stratosphere and mesosphere (110,000 to 250,000 feet).

9.157 Because the U.S.S.R. tests of high-yield nuclear weapons have been carried out in the Arctic and north temperate regions, the stratospheric fallout has come to earth more rapidly, and is consequently relatively more radioactive, than that from U.S. tests in the tropical Pacific Ocean area. If all other factors are equal, the fallout time is greatest when injection occurs in the spring. The half-residence time of material injected into the polar stratosphere is especially susceptible to this seasonal effect; for the north polar region, the time has been estimated to range from 3 months to 8 months depending upon whether injection takes place in December or April, respectively.

9.158 Regardless of where it is injected, the major portion of the stratospheric fallout will reach the earth in the temperate latitudes. This is mainly due to high-rainfall regions near the polar fronts (§9.146). Since the half-residence time in the troposphere is so short, air coming down through the tropopause gap or on its poleward side and moving toward the equator will be depleted of its contaminated particles by scavenging before it can reach the tropics. Consequently, stratospheric fallout in the equatorial zone is low in spite of the heavy rainfall.

9.159 Stratospheric debris originating in a particular hemisphere will tend to fall out in that hemisphere. For example, material injected at 10° N latitude was found to be distributed in such a way that two-thirds remained in the Northern Hemisphere. Since most nuclear tests have been performed in this hemisphere, the amount of delayed fallout on the ground is considerably greater than in the Southern Hemisphere (§9.168). In the event that the radioactive cloud reached a height of 100,000 feet in the stratosphere, it is probable that there would be more effective mixing of the air between the two

[8] The time to remove 80 percent is 2 32 effective half-residence times.

hemispheres, provided the injection did not occur in the polar regions.

9.160 The particles in the stratosphere are effectively held in storage, for periods of several months up to a few years, at the time when their radioactivity is greatest. During this interval, the radioactive debris does not represent a direct hazard and, in fact, most of the activity of short life decays away almost completely.[9] On the other hand, isotopes with long half-lives, such as strontium-90 and cesium-137, are not materially reduced in amount. As mentioned earlier, this is one of the significant aspects of the delayed fallout.

Fallout from Nuclear Weapons Tests

9.161 During the course of major nuclear weapons testing, from 1945 through 1958, approximately 92 megatons of fission yield were introduced into the atmosphere, to constitute both early and delayed fallout. The distribution according to nations and types of burst is given in Table 9.161. This table does not include data for tests carried out since 1958. In estimating fission yields a value of 50 percent has been chosen for the fission fraction of all thermonuclear devices, including those of the U.S.S.R., since this is about the average for the U.S. and U.K. tests.

9.162 For making estimates of delayed fallout, it is the general practice to determine the amount of strontium-90, for several reasons. It has a long half-life compared to the residence time in the stratosphere, so that it does not decay to any great extent prior to its deposition on the earth; it is produced in relatively large quantities in fission, and it is fairly easy to identify and measure by standard radiochemical techniques. Furthermore, the concentration of strontium-90 is of special interest because it provides a measure of the hazard from delayed fallout (§ 11.178 *et seq*).

9.163 The activity of strontium-90, as of radioactive materials in general, is conveniently expressed in terms of a unit called the "curie." It is defined as the quantity of any radioactive substance undergoing 3.7×10^{10} disintegrations per second. (This particular rate was chosen because it is close to the rate of disintegration of 1 gram of radium.) Where large amounts of active material are involved, the "megacurie" unit is employed; this is equal to 1 million curies and corresponds to disintegrations at the rate of 3.7×10^{16} per second. A megacurie of

[9] During the period of high delayed fallout rate in the spring of 1959, which reached the ground relatively soon after the U.S.S.R. test series of October 1958, appreciable activity resulted from the presence of the relatively short-lived isotopes zirconium-95, ruthenium-103 and -106, and cerium-141 and -144.

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strontium-90 is that quantity of this isotope which emits 3.7×10^{16} beta particles per second.[10]

9.164 The strontium-90 produced by weapons testing has been apportioned approximately as follows: mesosphere, 0.4 megacurie; lower stratosphere, 5.5 megacurie (3.0 U.S. and U.K., 2.5 U.S.S.R.);

TABLE 9.161

FISSION AND TOTAL YIELDS FROM NUCLEAR TESTS MADE BY THE UNITED STATES, THE UNITED KINGDOM, AND THE U.S.S.R. (1945–1958)

United States and United Kingdom Nuclear Tests

Years	*Fission yield (kilotons)*	*Fission yield from events with total yields of 1 MT or greater (kilotons)*
1945	60	---------
1946	40	---------
1948	100	---------
1951	500	---------
1952–1954	37, 000	36, 000
1955	200	---------
1956	9, 000	8, 000
1957–1958	19, 000	14, 000

U.S.S.R. Nuclear Tests

Years (inclusive)	*Fission yield (kilotons)*
1945–1951	60
1952–1954	500
1955–1956	4, 000
1957–1958	21, 000

All Nuclear Tests

Inclusive years	*Fission yield (kilotons)*			*Total yield (kilotons)*	
	Air burst	*Ground surface burst*	*Water surface burst*	*Air burst*	*Surface burst*
1945–1951	190	550	20	190	570
1952–1954	1, 000	15, 000	22, 000	1, 000	59, 000
1955–1956	5, 600	1, 500	6, 000	11, 000	17, 000
1957–1958	31, 000	4, 400	4, 600	57, 000	28, 000

troposphere, 0.6 megacurie; local Pacific Ocean, 2.7 megacurie. Of the 0.6-megacurie of tropospheric fallout, 0.5 megacurie probably fell into the sea within a few weeks, so that only about 0.1 megacurie descended on land areas. Consequently, any world-wide sampling of delayed fallout, which is made on land, will reflect mainly the 5.9 megacuries of strontium-90 from stratospheric fallout. Measurements in the continental United States west of the Mississippi River are

[10] *One megaton of fission yield produces about 0.1 megacurie of strontium-90.*

probably exceptional in this respect because of the tropospheric fallout of material originating at the Nevada Test Site. Thus, the strontium-90 content of the soil in this region is somewhat higher than that in other countries at the same latitude and with similar rainfall.

9.165 Since 1954, a number of sampling networks have been established in various parts of the world to determine the amounts of radioactive contamination in tropospheric and stratospheric air and in rainwater and soil, arising from weapons tests. The results obtained have shed a great deal of light on the possible mechanisms of the delayed fallout. The information so obtained, coupled with biological studies to determine the concentrations of certain radioisotopes in the diet and in human beings and animals, has permitted an evaluation to be made of the possible world-wide hazard (see Chapter XI).

9.166 The plots in Figs. 9.166 a and b show the variations over a period of years of the megacuries of strontium-90 present in the total stratospheric inventory, i.e., the amount still remaining in the stratosphere [11] at various times, and the ground inventory, i.e., the amount deposited on the ground. Calculations were made, using Fig. 9.149 to determine the quantity of strontium-90 injected into the stratosphere and the half-residence times given in § 9.156, together with weapons test yield data, for various scavenging conditions. It was found that best agreement with actual stratospheric and ground inventory determinations made since 1956 is obtained if it is assumed that on the average 50 percent of the strontium-90 activity from land surface bursts and 70 percent from water surface shots remains suspended in the atmosphere long enough to appear as delayed fallout. The plots in the two figures are based on these values.

9.167 The maximum amounts of strontium-90 in the earth's surface will be attained when the rate of natural radioactive decay just begins to exceed the rate at which the isotope reaches the ground in delayed fallout. While it appears that significant addition to the atmospheric inventory of strontium-90 may have been made during the latter part of 1961, it is estimated that the maximum surface accumulation from previous tests was attained in the summer of 1961. Subsequently, the surface inventory from these earlier tests will decrease. The estimated world-wide distribution of strontium-90 for the summer of 1961 is shown in Fig. 9.167. The quantities of this isotope are expressed in terms of its activity over a given area in units of millicuries per square mile, 1 millicurie being a one-thousandth part

[11] The stratospheric inventory does not include the material stabilized above 150,000 feet.

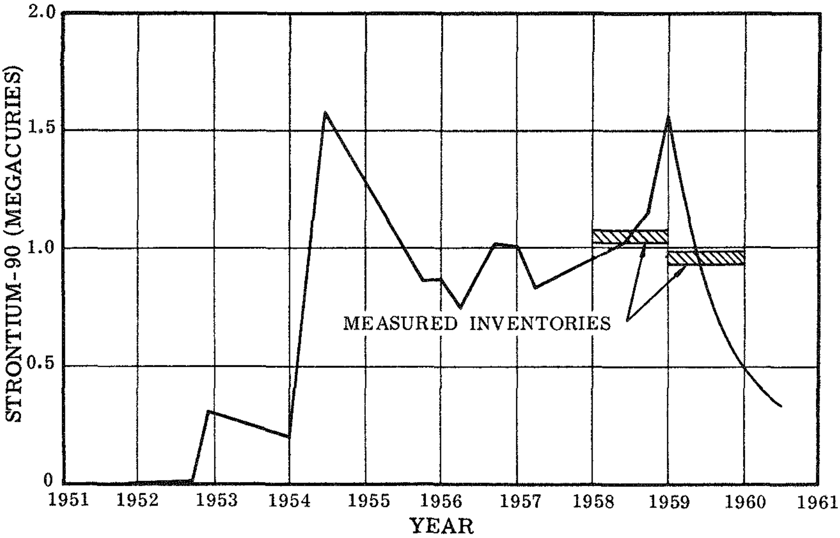

Figure 9.166a. Stratospheric burden (or inventory) of strontium-90.

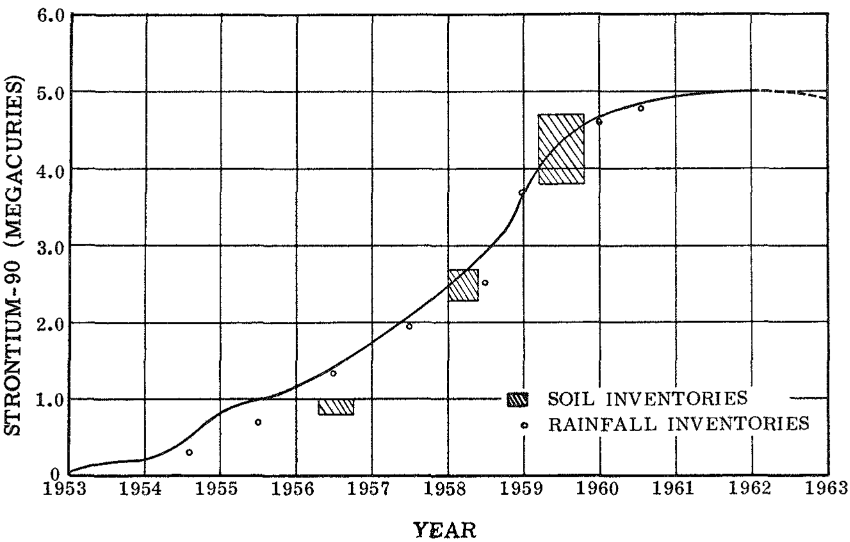

Figure 9.166b. Surface burden (or inventory) of strontium-90 from tests prior to September 1961.

of a curie[12] The mean annual rainfall for each 10° latitude is indicated at the top of the figure

9 168 The data illustrate some of the points relating to delayed stratospheric fallout mentioned earlier It is seen that most of the material, actually three-fourths of the total, is deposited in the Northern Hemisphere Moreover, in each hemisphere, the delayed fallout, as indicated by the strontium-90 activity, is greatest in the

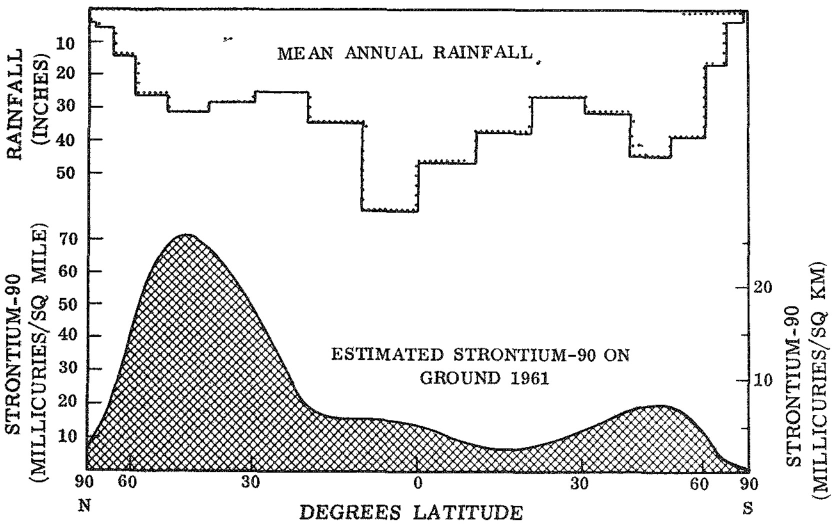

Figure 9 167 Estimated world-wide distribution of strontium-90 due to tests prior to September 1961, and mean annual rainfall

mid-latitudes (or temperate zone) where rainfall is high However, in the tropics, the strontium-90 activity is low, in spite of the very large mean annual rainfall for the reason given in § 9 158

9 169 After strontium-90, the next most important radioisotope from the biological standpoint is cesium-137 Fission products contain, after a short time, 1 8 times as many cesium-137 atoms as strontium-90 atoms Since there is essentially no fractionation relative to one another of these two isotopes and they have half lives which are not very different (§ 9 143), the activity of cesium-137 on the ground can be determined, to a good approximation, by multiplying the values for strontium-90, e g , Fig 9 176, by 1 8 The genetically

[12] If 1 megaton of fission yield were spread uniformly over one hemisphere of the earth the strontium 90 activity would be close to 1 millicurie per square mile

significant 30-year gamma ray dose from external cesium-137 in fallout from testing through the year 1958 will be no more than about 0.7 percent of the natural background radiation (§ 11.97). Isotopes of shorter half-life will increase the external dose to no more than about 1.7 percent of the background value (§ 11.190).

TECHNICAL ASPECTS OF RESIDUAL NUCLEAR RADIATION [13]

Rate of Decay of Fallout Activity

9.170 The continuous curves in Figs. 9.16 a and b, which represent the decrease in dose rate due to gamma radiation from radioactive fallout, have been obtained by summing the contributions of the more than 200 isotopes in the fission products and of the activity induced by neutrons in the weapons materials for various times after fission. The effects of fractionation, resulting from the partial loss of gaseous krypton and xenon (and their daughter elements) and from other circumstances, have also been taken into account (§ 9.08). The dose rates calculated in this manner vary with the nature of the weapon, but the values plotted in Figs. 9.16 a and b are reasonable averages for situations in which the fallout activity arises mainly from fission products. It is seen that the decrease in the dose rate with time cannot be represented by a simple equation which is valid at all times, but it can be approximated by the dashed straight lines labeled "$t^{-1.2}$", for times between 30 minutes to about 5,000 hours (200 days) after the explosion, to within 25 percent. For times longer than 200 days, the fallout decays more rapidly than indicated by the $t^{-1.2}$ line, so that the continuous curve may be used to estimate dose rates from fallout at these times.

9.171 During the interval in which the approximation is applicable, the decay of fallout activity at a given location may be represented by the simple expression

$$R_t \approx R_1 t^{-1.2}, \tag{9.171.1}$$

where R_t is the gamma radiation dose rate at time t after the explosion and R_1 is the dose rate at unit time; this is the unit-time reference dose rate which has been used earlier, e.g., in Figs. 9.16 a

[13] The remaining sections of this chapter may be omitted without loss of continuity.

and b, and Figs. 9.20 and 9.26. The actual value of R_1 will depend on the units in which the time is expressed, e.g., minutes, hours, days, etc. In this chapter, time is generally expressed in hours, so that the unit time for the reference dose rate R_1 is 1 hour.[14]

9.172 It should be clearly understood that equation (9.171.1) is applicable provided there is no change in the quantity of fallout during the time interval under consideration. It cannot be used, therefore, at such times that the fallout is still descending, but only after it is essentially complete, at the particular location. If any fallout material is removed in any way, e.g., by weathering or by washing away during the time t, or if any additional material is brought to the given point by wind or by another nuclear detonation, equation (9.171.1) could not be employed to determine the rate of decay of the fallout activity.

9.173 By rearranging equation (9.171.1) and taking, logarithms it follows that

$$\log \frac{R_t}{R_1} \approx -1.2 \log t, \tag{9.173.1}$$

so that a logarithmic plot of R_t/R_1 against t should give a straight line with a slope of -1.2. When $t=1$, i.e., 1 hour after the explosion, $R_t=R_1$ or $R_t/R_1=1$; this is the basic reference point through which the straight line of slope -1.2 is drawn in Figs. 9.16 a and b.

9.174 The total dose received from a given quantity of fallout can be determined from Fig. 9.20 using the method described in § 9.21. The curve in Fig. 9.20 was obtained by numerical integration of the actual dose-rate (continuous) curve in Figs. 9.16 a and b. However, for times between 0.5 hour (30 minutes) and 5,000 hours (200 days) after the explosion, it is sometimes convenient to have an analytical expression for the dose received during a given time interval. Such an approximate expression can be obtained by direct integration of equation (9.171.1); thus if D is the total dose received between the times t_a and t_b, then

$$D \approx R_1 \int_{t_a}^{t_b} t^{-1.2}\, dt = 5R_1(t_a^{-0.2} - t_b^{-0.2}). \tag{9.174.1}$$

Hence if the unit-time reference dose rate R_1 is known, or is determined by using Figs. 9.16 a and b, and the observed dose rate at any known time after the explosion, the total (or accumulated) dose for

[14] Physically the unit-time reference dose rate is the dose rate that would have been received from the given (constant) amount of fallout at unit time, e.g., 1 hour after the explosion, although this quantity might actually have been in transit at that time and would not have reached the location under consideration.

any required period can be calculated, provided the fallout activity decays in accordance with the $t^{-1.2}$ relationship during this period.

9.175 Measurements made on actual fallout from weapons tests indicate that, although the $t^{-1.2}$ decay represents a reasonable average, there have been instances where exponents in the range of -0.9 to -2.0, rather than -1.2, are required to represent the rate of decay. In fact, different exponents are sometimes needed for different times after the explosion. These anomalies apparently arise from the particular circumstances of the explosion and are very difficult to predict, except possibly when a large quantity of neutron-induced activity is known to have been produced. Furthermore, fallout from two or more explosions occurring at different times will completely change the observed decay rate. In general, too, over a long period of time after the burst, weathering will tend to alter the dose rates in an unpredictable manner. Consequently, in an actual situation following a nuclear detonation, estimates based on either the $t^{-1.2}$ decay rule or even on the continuous curves in Figs. 9.16 a and b must be used with caution and should be verified by actual measurements as frequently as possible.

9.176 Within the limits of applicability of the $t^{-1.2}$ decay relationship, equation (9.171.1) or (9.173.1) can be used to determine the time which an individual can stay in a location contaminated by fission products without receiving more than a specified dose of radiation. In this case, the total dose is specified; t_a is the known time of entry into the contaminated area and t_b is the required time at (or before) which the exposed individual must leave. In order to solve this problem with the aid of equation (9.174.1), it is necessary to know the unit-time reference dose rate R_1. This can be obtained from equation (9.171.1) if the dose rate, R_t, is measured at any time, t, after the explosion, e.g., at the time of entry. The results can be expressed graphically as in Figs. 9.26 and 9.27.

9.177 In principle, equation (9.173.1) could be used to estimate the total dose received from fallout in a contaminated area, provided the whole of the fallout arrives in a very short time. Actually, the contaminated particles may descend for several hours, and without knowing the rate at which the fission products reach the ground, it is not possible to make a useful calculation. When the fallout has ceased, however, equations (9.171.1) and (9.174.1) may be employed to make rough estimates of radiation doses over moderate periods of time, up to about 200 days after the explosion, provided one measurement of the dose rate is available.

Radiation Dose Over Contaminated Surfaces

9.178 It was seen in § 9.163 that the curie and megacurie are useful units for expressing the activity of radioactive material, and they will now be employed in connection with the contamination of areas. Because, as far as the external radiation dose is concerned, the gamma rays are more significant biologically than the beta particles, the early fallout activity may be stated in gamma-megacuries, as a measure of the rate of emission of gamma-ray photons, where 1 gamma-megacurie represents the production of 3.7×10^{16} photons per second.

9.179 If an area is uniformly contaminated with any radioactive material of known activity (in gamma-megacuries) at a given time, it is possible to calculate the gamma-radiation dose rate at various heights above the surface, provided the average energy of the gamma-ray photons is known. The results of such calculations, assuming a contamination density of 1 gamma-megacurie per square mile, for gamma rays having various energies, are represented in Fig. 9.179. If the actual contamination density differs from 1 megacurie per square mile, the ordinates in the figure would be multiplied in proportion.

9.180 The calculations upon which Fig. 9.179 is based take into account the effects of "skyshine" (§ 8.40). Furthermore, it is assumed that the surface over which the contamination is distributed is perfectly smooth and infinite in extent. For actual terrain, which is moderately rough and may have a variety of radiation shielding, the dose rate at a specific height above the ground would be less than for an infinite, smooth plane. The actual reduction factor will, of course, depend on the terrain features and the extent of the contaminated area. As a rough approximation, a factor of 0.7 is commonly applied to the dose rates obtained from Fig. 9.179 to obtain average values for a moderately rough terrain.

9.181 The dose rate at greater heights above the ground, such as might be observed in an aircraft, can be estimated with the aid of Fig. 9.181. The curve gives approximate values of the attenuation factor for early fallout radiation as a function of altitude. It applies in particular to a uniformly contaminated area that is large compared to the altitude of the aircraft. If the dose rate near, i.e., 3 feet above, the ground is known, then the value at any specified altitude can be obtained upon dividing by the attenuation factor for that altitude. On the other hand, if the dose rate is measured at a known altitude, multiplication by the attenuation factor gives the dose rate at about 3 feet above the ground at that time.

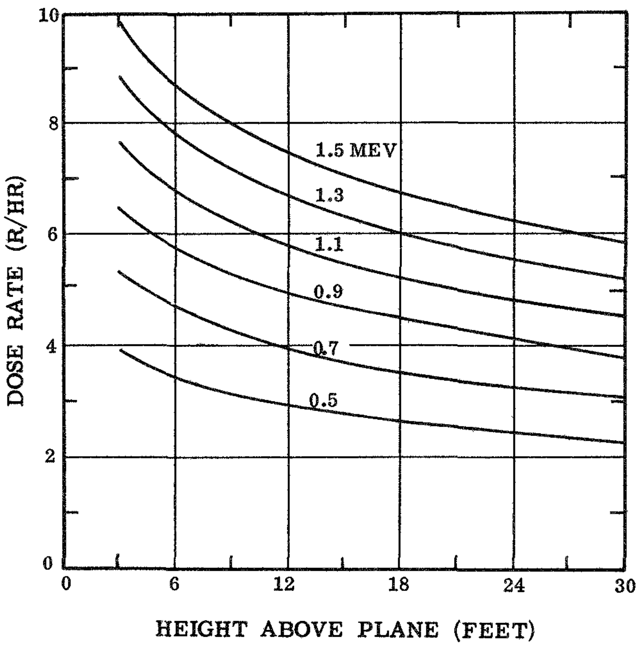

Figure 9.179. Dose rates above an ideal plane from gamma rays of various energies for a contamination density of 1 gamma-megacurie per square mile.

9.182 A possible use of the curve in Fig. 9.181 is to determine the dose rate near the ground and contamination density from data obtained by means of an aerial survey (see § 12.59). For example, suppose a radiation measuring instrument suspended from an aircraft at a height of 1,000 feet showed a radiation dose of 0.24 roentgen per hour (r/hr) and that, from the known time after the explosion, the average energy of the gamma-ray photons was estimated to be 0.8 Mev. The attenuation factor for an altitude of 1,000 feet is approximately 27 and so the dose rate at 3 feet above ground at the time of the observation is roughly $0.24 \times 27 = 6.5$ r/hr. It is seen from Fig. 9.179 that for a contamination density of 1 megacurie per square mile and a photon energy of 0.8 Mev, the dose rate 3 feet above the ground would be about 5.9 r/hr. Hence, in the present case, the contamination density of the ground is approximately $6.5/5.9 = 1.1$ gamma-megacurie per square mile.

9.183 It has been calculated that, on the average, the total gamma-ray activity from the fission products produced by a 1-kiloton TNT equivalent fission explosion would be about 550 gamma-megacuries

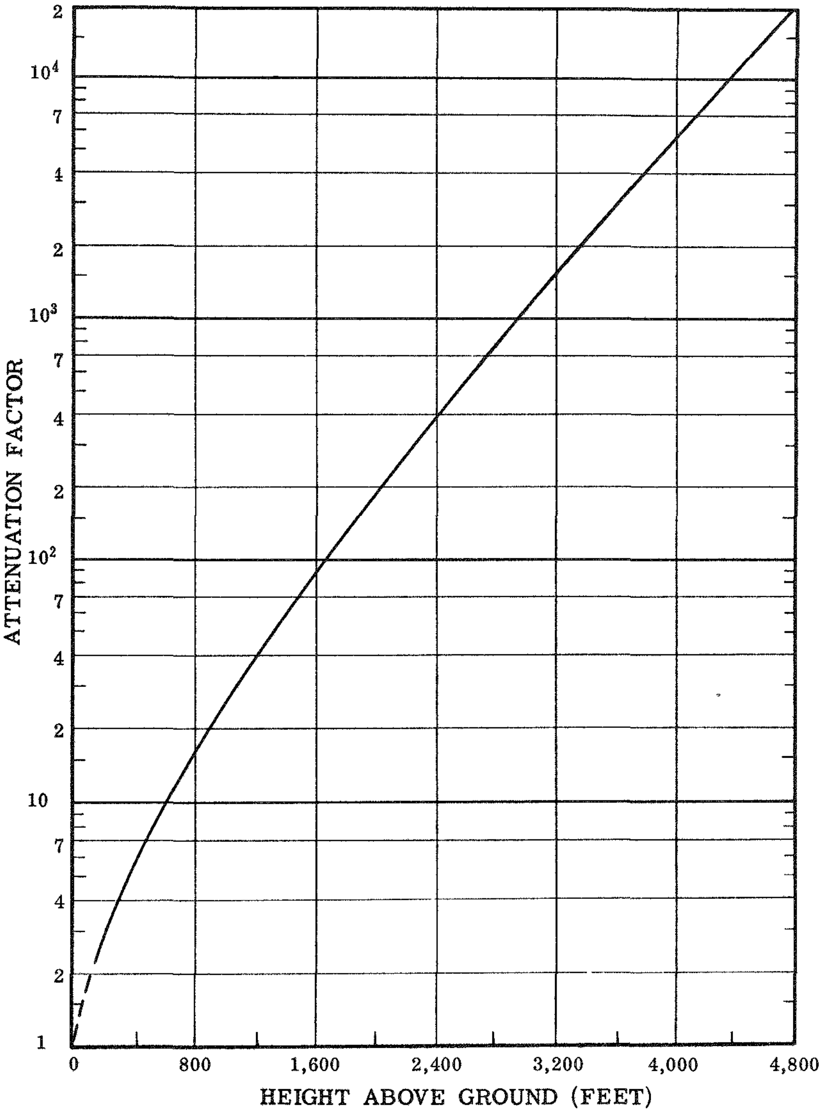

Figure 9.181. Altitude attenuation factor for early fallout radiation dose rate 3 feet above the ground.

at 1 hour after the explosion. If this activity were spread uniformly over a smooth plane 1 square mile in area then, assuming a mean photon energy of 0.95 Mev, the radiation dose received at a point 3 feet above the plane can be estimated from Fig. 9.179 as roughly

6.8×550, i.e., approximately 3,700 r/hr. Activity induced by neutron capture in the weapon materials may add about 200 r/hr to this figure. Hence, if 100 percent of the radioactivity present in the weapon debris were deposited uniformly over a smooth surface of area 1 square mile, the 1-hour dose rate above this area would be about 3,900 r/hr per kiloton of fission yield. This means that if the same residues were spread uniformly over a smooth surface of A square miles in area, the 1-hour dose rate would be 3,900/A r/hr; consequently, the product of the 1-hour dose rate and the area in square miles would be equal to 3,900 in units of (r/hr)(sq mi) per kiloton. If all the residues from 1-kiloton fission yield were deposited on a smooth surface in varying concentrations typical of an early fallout pattern, instead of uniformly, the product of the dose rate at 1 hour and the area would be replaced by the "area integral" of the 1-hour dose rate defined by

$$\text{Area Integral} = \int_A R_1 dA,$$

where R_1 is the 1-hour dose rate over an element of area dA and A square miles is the total area covered by the residues. Hence, regardless of the concentration pattern, the area integral of the 1-hour dose rate over a smooth surface would always be 3,900 in units of (r/hr)(sq mi) per kiloton of fission, assuming that the fallout particles had been completely deposited at that time.

9.184 Measurements of the early fallout pattern resulting from the BRAVO test (§ 9.100), made with radiation monitoring instruments 1 week after the detonation, are consistent with values in the range of 1,000 to 1,500 (r/hr)(sq mi) per kiloton of fission yield for the 1-hour dose rate area integral. This differs from 3,900 (r/hr)(sq mi)/kt given above, for two main reasons: first, only part of the radioactivity of the weapon residues appears in the early fallout, and second, corrections must be applied to the measured value for instrument response and terrain shielding. A typical ionization-chamber monitoring instrument, calibrated and used in the usual manner, will read about 25 percent too low, because of its directional response and shielding provided by the operator. This correction increases the observed mean of the area integral to 1,700 (r/hr)(sq mi)/kt. An average value of the terrain shielding factor, i.e., the ratio of the actual dose rate to that which would exist above an ideal smooth surface, is taken to be 0.7. On this basis, the 1-hour dose rate area integral over an ideal smooth plane, with no shielding, would be approximately 2,400 (rh/hr)(sq mi)/kt. The ratio of this number to the theoretical 3,900 (rh/hr)(sq mi)/kt indicates that some 60 percent of the total

gamma-ray activity of the weapon residues is deposited in the early fallout from a land surface burst (§ 9.48). This value must be recognized as an estimate because the data available are somewhat limited.

9.185 It should be noted that integration over the whole area of the idealized fallout pattern in Fig. 9.73 gives a value of approximately 1,700 (rh/hr)(sq mi)/kt for the 1-hour dose rate. The data thus refer to actual dose rates, i.e., after instrument correction, which would be expected over moderately flat terrain with a shielding factor of 0.7. In a city, the values might be 70 or 75 percent of those in Fig. 9.73, because of the increased shielding of buildings, trees, etc. (§ 9.92).

Rate of Particle Fall

9.186 The time at which particles of a given size and density will arrive at the ground from specified heights in the nuclear cloud may be calculated from aerodynamic equations of motion. The effects of vertical air motions are generally ignored since they cannot be predicted, especially as they are believed to be generally small for particles which fall within 24 hours. However, field test data sometimes indicate times of arrival which are quite different from those predicted by the theoretical calculations; hence, it is probable that vertical wind components and other factors may sometimes significantly influence the particle fall.

9.187 Some typical results of time of fall calculations are shown in Fig. 9.187. The curves give the times required for particles of different sizes to fall to earth from various initial altitudes. The density of the fallout material is taken to be 2.5 grams per cubic centimeter, which is roughly that of dry sand; the falling particles are assumed to be spherical, their radii being given in microns (μ). Actual fallout particles are sometimes quite irregular and angular in shape, although a large percentage tend to be fairly smooth and globular since they result from the solidification of fused spherical droplets of earth and of weapon debris. Even if the particles are irregular, they can be assigned an effective radius and then treated as spheres for calculating times of fall.

9.188 The percentages given in Fig. 9.187 represent estimates of the proportions of the total activity deposited by particles with sizes lying between pairs of lines. Thus, particles with radii larger than 200 microns carry 1 percent of the activity; those between 150 and 200 microns carry 3 percent, and so on; at the other extreme, particles less than 20 microns in radius carry 12 percent of the activity. This distribution of activity is known as "log-normal" because it obeys the

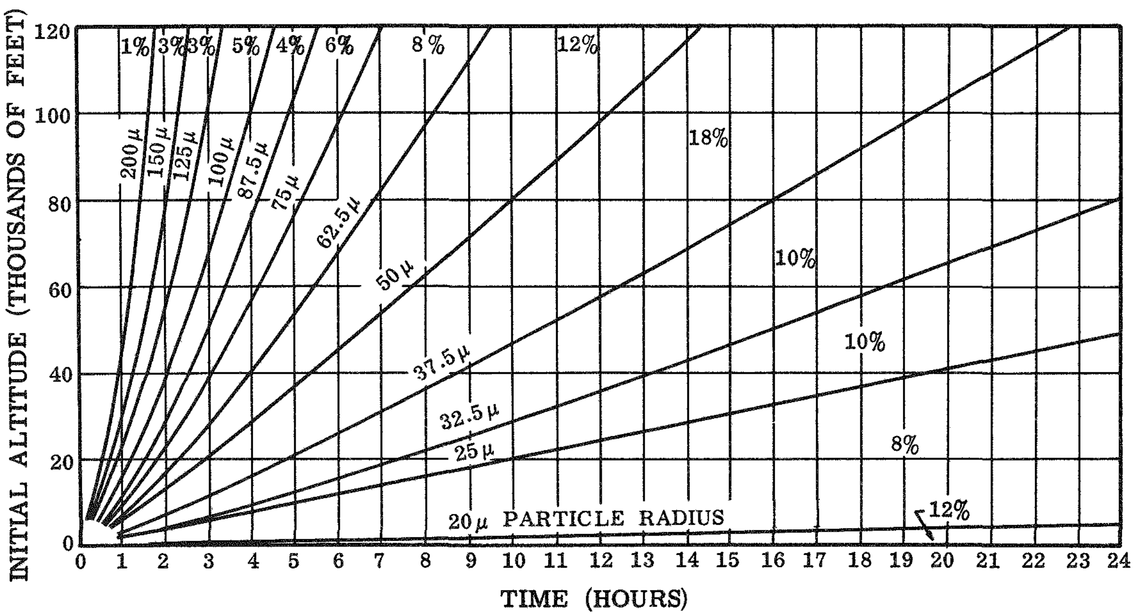

Figure 9.187. Times of fall of particles of different sizes from various altitudes and percentages of total activity carried.

normal (Gaussian) distribution law with the logarithm of the particle radius as the variable. It may not be strictly valid in any given case, since the activity distribution varies with the type of burst, the nature of the terrain at ground zero, etc. Nevertheless, it is characteristic of the activity distributions assumed for the theoretical analysis of fallout.

9.189 The arrival time at a location downwind from a nuclear explosion may be estimated if the effective wind velocity in the intervening space is known. It is equal to the downwind distance from the near edge of the stabilized radioactive cloud divided by the effective wind speed. Consider, for example, a point located 300 miles downwind from the explosion and suppose the effective wind speed is 15 miles per hour. The time of arrival of fallout at the point under consideration would then be 300/15=20 hours. If the mushroom cloud stabilizes at 60,000 feet, then it follows from Fig. 9.187 that, by this time, only particles with radii less than about 30 microns will still be present, and that they carry roughly 25 percent of the total activity deposited in the early fallout. It is evident that, in spite of the decay which will have occurred in transit, fallout of appreciable activity may be expected 300 miles downwind at about 20 hours after the detonation.

9.190 At the time of arrival at a downwind location, the dose rate will begin to rise, as shown in Figs. 9.71 a and b. Subsequently, the dose rate will fall and, when the early fallout is essentially complete, decay will occur roughly in accordance with the $t^{-1.2}$ rule. Exceptions to this behavior could result from unusual wind shears or precipitation after the maximum dose rate has been reached; these could produce a second, possibly higher, maximum at a later time. It is this kind of phenomenon which is responsible for the production of hot spots in the early fallout distribution.

Prediction of Early Fallout Path

9.191 In addition to the methods for estimating fallout dosage patterns mentioned in § 9.60 *et seq.*, simple procedures have been developed for rapidly determining the expected path and approximate times of arrival of the fallout. One of these, which has proved quite useful in weapon tests, will be described here. The basic information required is an observation (or forecast) of the mean wind direction and speed in a series of 5,000-foot thick layers of the atmosphere from the earth's surface to the top of the radioactive cloud.

9.192 Starting at a point O, representing ground zero, in Fig. 9.192, a vector OA is drawn, indicating the direction and velocity (in miles

per hour) of the wind in the first 5,000-foot layer from the ground. This is followed by vectors *AB*, *BC*, . . ., *GH*, for successive layers up to the limit of observation, e.g., the top of the cloud, in this case, $8 \times 5{,}000 = 40{,}000$ feet. The line *OH* then represents the locus of particles which fall from a height of 40,000 feet at various times. The larger particles will be found close to ground zero, soon after the explosion, whereas the smaller particles fall at greater distances, at later times. The line *OG* is the locus of particles falling from a height of 35,000 feet, since these are not subjected to the wind represented by the vector *GH*. Similarly, *OF* is the locus for particles which begin to fall at 30,000 feet, and so on. The average wind for levels up to 40,000 feet is equal to the length of *OH* divided by the number of 5,000-foot layers, i.e., eight in this case.

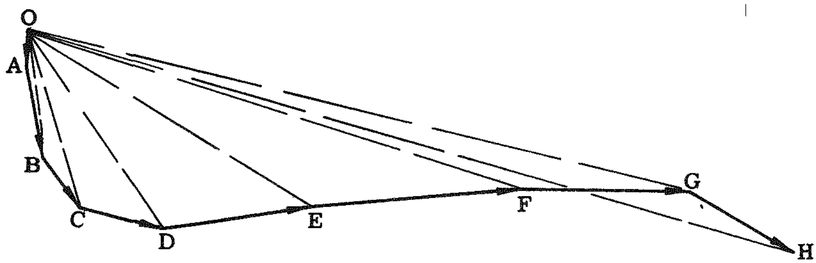

Figure 9.192. Prediction of approximate path of fallout based on wind pattern

9.193 The region enclosed by the line *OH* and the various vectors may thus be regarded as providing a rough indication of the general direction of the fallout with respect to ground zero. To account for the physical dimensions of the radioactive cloud, the vectors should be extended by one cloud radius (see Fig. 2.16) in all directions.

9.194 Although Fig. 9.192 gives a general idea of the shape of the fallout area, it does not indicate its overall extent. If, as in the case considered above, the wind vectors, expressed in miles per hour, are drawn at 5,000-foot intervals, *OH* is the distance traveled by particles descending from the height of 40,000 feet in 8 hours. Similarly, *OG* is the distance traveled by particles descending from 35,000 feet in 7 hours. Thus, *OAB* . . . *HO* is dimensionally the approximate area in which particles having diameters of 75 microns (or more) will descend. Such particles fall at the rate of 5,000 feet per hour (or more). Smaller particles fall more slowly and will be found outside the area shown. The loci on the ground of particles descending from

various heights will, however, have the same directions as before. Thus, particles with diameters less than 75 microns falling from 40,000 feet will appear along an extension of *OH*, those from 35,000 feet along an extension of *OG*. Hence, the general shape of the fallout pattern is related to that in Fig. 9.192, although it covers a larger area.

9.195 It will be apparent that the procedure just described can provide only a rough guide concerning the probable early fallout area. In actuality, the particle size distribution will not be known, and the height of the radioactive cloud from which the particles descend will not be very certain. In addition, the wind directions and velocities may change with time, and the effect of sharp wind shears in thin layers has been neglected. Finally, there is the fundamental assumption that the wind pattern used in drawing Fig. 9.192 applies to the whole area of significant contamination which may extend hundreds of miles from ground zero. Precipitation occuring at the time of (or soon after) the detonation may also change the fallout situation, since radioactive particles may become attached to the drops and descend from various heights at rates which are characteristic of the rain or snow.

9.196 Similar fallout area plots may be constructed from the UF (Upper-air Fallout) wind data which are reported by U.S. Weather Bureau upper-air observing stations two to four times daily. The UF method, developed by the Weather Bureau to meet civil defense requirements, has the great merit of simplicity and speed which make it ideal for use even under emergency conditions.

9.197 The UF "winds" indicate the direction and distance from ground zero where particles, falling from various levels in a nuclear explosion cloud (10, 20, 40, 60, and 80 thousand feet) and requiring 3 hours to reach the ground, will land. These "fallout vectors" are computed from the current upper wind observations. The estimated fallout area may be obtained by plotting the UF vectors from the burst point as shown in Fig. 9.197. The 3-hour isochrone, i.e., the locus of particles which take 3 hours to reach the ground from the various altitudes, may be drawn through the 3-hour points given in the UF wind report. The time of arrival of fallout at any point can be approximated by linear extrapolation of the distance from the burst point to the 3-hour line. It is recommended that extrapolations beyond 3 hours be made only for particles originating at 40,000 feet and above. Extrapolation beyond 12 hours is not recommended since the UF method does not take into account the time and space changes in the wind.

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9.198 In the event that no upper wind information at (or near) the time of the explosion is available, use may be made of the general pattern to be expected in the given location at the particular time of year. This information, based on observations made at weather stations over long periods, may perhaps be supplemented by visual estimates of the direction of cloud movements at various heights. It is important to emphasize that fallout patterns based on surface winds alone may be completely misleading.

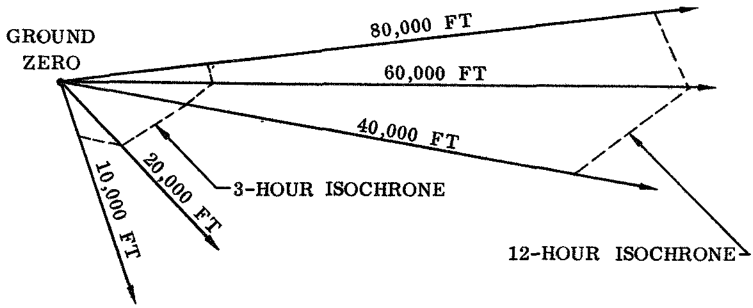

Figure 9.197. Simplified UF fallout area plot (radial lines indicate where fallout from the various levels is expected to occur).

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CHAPTER X

RADIO AND RADAR EFFECTS

INTRODUCTION

10.01 A nuclear explosion is accompanied by two principal types of electromagnetic effects.[1] These are entirely different from each other in nature, but both involve the whole spectral region of wavelengths longer than infrared, i.e., from about 1 millimeter on up to very large values. One involves the actual emission of an electromagnetic pulse of short duration from the explosion itself (or from the disturbed region in its vicinity), whereas the other, through alterations to the electrical properties of the atmosphere, can result in serious disturbance of electromagnetic waves, such as are used in communications and for radar, passing in the vicinity of the nuclear detonation. This disturbance may be caused by debris or water vapor introduced into the atmosphere by the burst, or by the unusual conditions created by the ionizing radiations from the exploding device. The latter mechanism may cause some radio and radar systems to be "blacked out" for several hours following the explosion. What little is known about the origin and characteristics of the electromagnetic pulse will be described first; the bulk of this chapter will then be concerned with a discussion of the changes in the normal ionization of the atmosphere brought about by a nuclear explosion and of the consequences of these changes.

THE ELECTROMAGNETIC PULSE

Origin of the Electromagnetic Pulse

10.02 The electromagnetic pulse or "radioflash" which is produced at the time of a nuclear detonation is of considerable interest. It is fairly well known that even small detonations of ordinary chemical

[1] The term "electromagnetic" as used in this chapter applies to radiations of the longer wavelengths and not to the entire spectrum described in § 1.69 *et seq.*, which is strictly included in the term.

explosives can produce electromagnetic signals, so it is not surprising that substantial pulses of this type accompany nuclear explosions.

10.03 There appear to be at least two different mechanisms whereby an electromagnetic pulse may be produced by a nuclear explosion. The first is associated with the creation by radiations from the burst of some kind of asymmetry in the electric charge distribution in the region surrounding the detonation; the second is the result of the rapid expansion of the essentially perfectly-conducting plasma of weapon residues in the earth's magnetic field. The first mechanism, often called the "Compton-electron model" for reasons which will be seen below, is believed to be the principal means for generation of electromagnetic pulses by detonations on or slightly above the earth's surface and by those near the "top" of the sensible atmosphere. The other, called the "field displacement" model, might be responsible for electromagnetic signals from underground bursts where the expansion is restrained in a more or less spherically symmetrical manner by the surrounding material, or from those at such great altitudes that the only immediate interaction of the explosion is with the geomagnetic field.

10.04 In the Compton-electron model the photons of the initial gamma radiation leave the exploding weapon with high energies, very soon collide with electrons in the atoms and molecules of the surrounding air, and transfer to them most of their energy. These Compton electrons (§ 8.68) move rapidly away, on the average, from the center of the burst. Provided some kind of asymmetry exists, this motion is apparently one of the main sources of the electromagnetic pulse. If the explosion were perfectly symmetrical, in a uniform atmosphere, the effects would be equal in all directions; the opposite components would then compensate each other exactly and there would be no electromagnetic signal. However, there are invariably a number of unrelated factors associated with a nuclear explosion which insures the presence of an asymmetry and, hence, of an electromagnetic pulse.

10.05 The most obvious asymmetric situation is that arising from a surface or near-surface (within 350 feet or so) burst, where the presence of the earth itself confines expansion of the weapon residues and radiation emission to the upward hemisphere. At the other extreme, where the explosion takes place high in the atmosphere, there will be very little interaction by upward-moving gamma rays because of the low air density, whereas those going downward will produce Compton electrons within a moderate distance. In both these cases, though their detailed behavior is probably different and their directions are opposite, the effective Compton-electron pulse is essentially

vertical. Moreover, no matter where the burst occurs, there is inevitably some asymmetry in the emission and interaction of the photons. For example, the gamma-ray flux from an exploding weapon is itself never fully symmetric because of the presence of auxiliary apparatus, external structure, or the carrying vehicle. It should be noted that, while the "natural" asymmetries tend to be vertical, the other type may be oriented in any direction.

10.06 The Compton electrons created by the initial gamma radiation thus move away asymmetrically, at high velocity, from the exploding weapon. Since the remaining symmetrical components still compensate each other's effects, this motion appears from a distance to be a practically instantaneously accelerated pulse of current in one direction; it is, in other words, something like an "electric dipole" radiator of classical electrodynamics. The current pulse in the air radiates electromagnetic energy just as it would if it were flowing in a wire transmitting antenna, and this radiation constitutes the first part of the characteristic signal of the explosion.

10.07 When the Compton electrons move away from the explosion they leave behind the much slower moving positive ions, which are the other component of the ion pairs (§ 8.16). This relative displacement of positive and negative charges produces a radial electric field. In addition, in its passage through the air each Compton electron itself produces a large number of electron-ion pairs, perhaps 30,000, mostly toward the end of its path of 10 to 15 feet. Under the influence of the radial electric field, the large number of electrons now present will be driven back toward the burst point. This initiates a second pulse of current, but it is rapidly terminated by recombination of electrons with ions and by attachment of the electrons to neutral atoms and molecules in the air, even before the electric field is neutralized. The negative ions produced in the attachment process, and a corresponding number of positive ions, remain free a while longer because the ions, being heavier and less mobile than electrons, collide less frequently. This large volume of ionized gas (or "plasma") undergoes oscillations at characteristic frequencies similar to those observed in experimental plasmas in the laboratory. The oscillations damp out in a short time, as the negative particles (ions and electrons) combine with positive ions, but while they last they produce electromagnetic waves in the radiofrequency range.

Characteristics of the Compton-Electron Signal

10.08 The effective rise-time of the main part of the initial signal pulse (produced by the Compton electrons) from surface or near-

surface bursts is of the order of 10^{-8} second, so that oscillation frequencies as high as 100 megacycles (10^8 cycles) per second may be expected. However, only a very small part of the total electromagnetic energy radiated is carried at such high frequencies. In addition, the higher frequencies are attenuated much more rapidly than the lower ones in normal propagation through the atmosphere. The frequencies of the plasma oscillations, which continue for several milliseconds and radiate considerably more energy, are much lower. These frequencies are attenuated hardly at all in normal propagation. At the lower end of the spectrum are the extremely low frequencies (in the very low kilocycle region) which might be detected very close to any such excited radiating dipole; they would exist principally in the "induction" and "quasi-static" fields and not be radiated at all.

10.09 The electromagnetic signal, as detected at a range of a hundred miles or so, thus consists of a continuous spectrum with most of its energy distributed about a median frequency (10 to 15 kilocycles per second) which is related inversely to the yield. At much longer distances, of many hundreds or thousands of miles, the form and spectrum of the pulse are determined largely by the characteristics of the medium of propagation, i.e., the "duct" between the surface of the earth and the D- or E-region of the ionosphere (see § 10.16).

10.10 A somewhat similar explosively-excited vertical dipole radiator which is frequently encountered in nature is lightning, and the electromagnetic signal (or static) associated with lightning also has a peak in the region of 10 kilocycles. This must not be taken, however, to mean that there is a detailed similarity in the modes of generation of the electromagnetic signals from lightning discharges and from nuclear explosions. The transmission path largely obliterates the characteristics of the original signal in both cases.

The Field-Displacement Mechanism

10.11 The second possibility which has been mentioned for the generation of radiofrequency signals by a nuclear explosion is considered to be of particular significance for extremely-high-altitude bursts. Immediately after the detonation has occurred, the hot weapon debris is essentially a highly ionized vapor (or plasma) which is expanding rapidly. A property possessed by all plasmas is a tendency to exclude a magnetic field, such as that of the earth, from its interior. The expanding plasma of weapon residues thus

causes a violent distortion of the earth's magnetic field. As a result of the interaction between the geomagnetic field and the charged particles in the expanding plasma and in the very tenuous, largely ionized, surrounding gases, this disturbance propagates away from the burst region as a "hydromagnetic wave".

10.12 The hydromagnetic wave retains its identity and characteristics in propagating over very long distances at high altitudes, but at lower levels, where it interacts with the denser atmosphere, it is detected as an ordinary electromagnetic wave or magnetic disturbance. The field-displacement mechanism is believed to be especially important at very high altitudes where the air density is low and the expansion of the debris is not impeded by the atmospheric pressure. It is probable that the same mechanism may operate to produce an electromagnetic signal from an underground burst. The expansion of the debris is here limited to a few yards and the signal is therefore small, but it may be detectable at short ranges.

ATMOSPHERIC IONIZATION PHENOMENA

Effects of Ionization on Radio Signals

10.13 Ionization, that is, the formation of ion pairs consisting of separated electrons and positive ions (§ 8.16), can be produced, either directly or indirectly, by the gamma rays and neutrons of the initial nuclear radiation, by the beta particles and gamma rays of the residual nuclear radiation, and also by the X-rays and even the ultraviolet light present in the primary thermal radiation (§ 2.38). Hence, after a nuclear explosion, the density of electrons in the atmosphere in the vicinity is greatly increased. These electrons can affect electromagnetic (radio and radar) signals in at least two ways. First, under suitable conditions, they can remove energy from the wave and thus attenuate the signal; second, a wave front traveling from one region into another in which the electron density is different will be refracted, i.e., its direction of propagation will be changed. It is evident, therefore, that the ionized regions of the atmosphere created by a nuclear explosion can influence the behavior of communications or radar signals whose transmission paths encounter these regions.

10.14 When a free electron is exposed to a radiofrequency wave, some of the energy of the wave is transferred to the electron as energy of vibration. If the electron does not lose this energy as the result of a collision with a neutral particle (atom or molecule) in the air, it will

radiate a new electromagnetic signal at the same frequency. Thus the energy is restored to the wave without loss. If, however, the air density is appreciable, e.g., more than about one ten-thousandth of the sea-level value, collisions between electrons and neutral particles will take place at a significant rate. In such collisions, most of the excess (vibrational) energy of the electron is transformed into random kinetic energy and cannot be re-radiated. The result is that energy is absorbed from the wave and the electromagnetic signal is attenuated.

10.15 It is apparent, therefore, that marked loss of signal strength will occur only when the electron density and air density are both moderately large. Other conditions being held constant, more energy is absorbed by an ionized gas as the frequency of the signal is decreased. Both positive and negative ions can, in principle, absorb electromagnetic energy in the same way as do electrons, but their larger mass makes them much less effective. It is permissible, therefore, to disregard the ions in this connection.

Ionization in the Normal Atmosphere

10.16 In order to understand the effects of free electrons on radio and radar systems, it is necessary to review briefly the ionization in the normal, undisturbed atmosphere. Below an altitude of about 40 miles, there is little ionization, but above this level there is a region called the "ionosphere", in which the density of free electrons (and ions) is appreciable (see Fig. 9.145). The ionosphere consists of three, more or less distinct, layers, called the D-, E-, and F-regions. In the daytime, especially in summer, the F-region is split up into two layers, called F_1 and F_2; for the present purpose, however, this division may be disregarded. The electron density does not increase gradually from one region to the next, but in each region there is a broad maximum (or peak) density; the value of this maximum increases from the D- to E- to F-regions, that is, with increasing altitude (Fig. 10.16).

10.17 The electrons (and ions) in the normal ionosphere are produced by interaction of solar radiations with various atomic and molecular species in the atmosphere, and they are removed either by recombination with positive ions or by attachment to neutral particles. The former process is the more important when the electron density is high, but the latter is favored by an increase in the density of the air.

10.18 For altitudes below 30 or 35 miles, the air is relatively dense and the probability of collisions between free electrons and atmospheric

atoms and molecules is large. As a result, the electrons are rapidly removed by attachment to neutral particles and the average lifetime of a free electron in this region is less than a millionth of a second, i.e., a microsecond. Any ionization produced will thus disappear very rapidly, and the electron density will be small and the effect on electromagnetic signals negligible.

10.19 In the altitude range from roughly 40 to 50 miles (D-region of the ionosphere), the density of neutral particles (molecular nitrogen

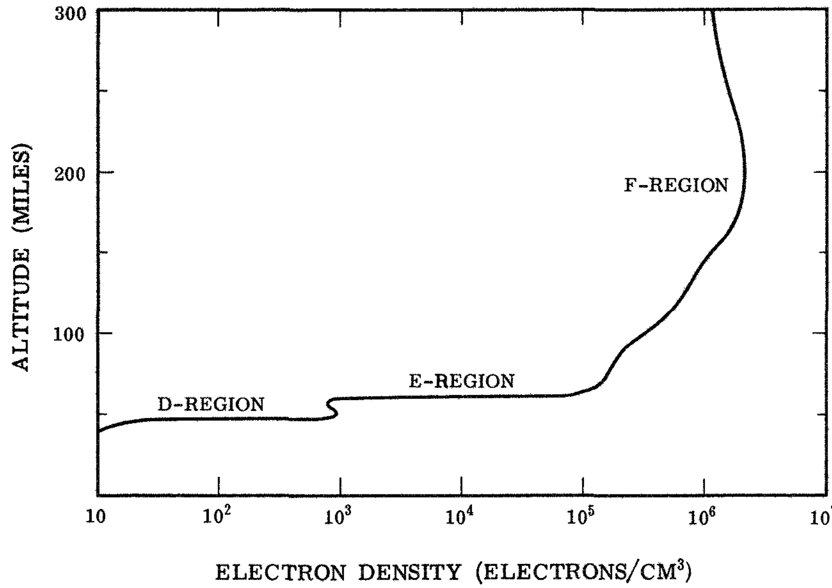

Figure 10.16. Electron densities in D-, E-, and F-regions of the ionosphere in the daytime.

and oxygen mainly, and some nitric oxide and atomic oxygen) is sufficiently small—about 10^{-4} times the sea-level density of the air—to allow electrons to remain free for several minutes. The average lifetime varies with location and the time of the year, but it is long enough for the radiation from the sun to maintain a peak density of about 10^3 electrons per cubic centimeter in the daytime. At night, when electrons are no longer being generated by solar radiations, the free electrons disappear. Although the density of neutral particles is small enough to permit the electrons (in the daytime) to have an appreciable average life, it is nevertheless sufficiently large for col-

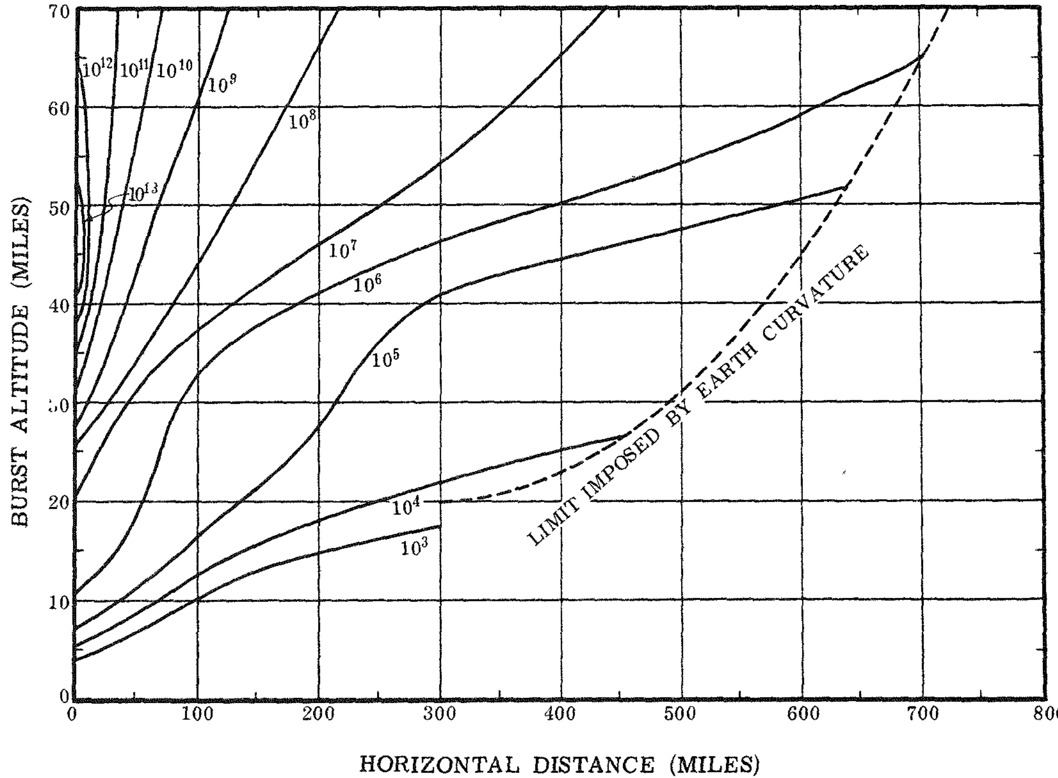

Figure 10.29. Calculated electron densities at an altitude of 45 miles produced by 1-megaton fission yield explosion at various burst heights as a function of horizontal distance.

of several thousand miles; as stated above, the distance over which ionization occurs is limited, however, by the curvature of the earth. For a detonation at 70 miles, for example, the earth's curvature prevents radiation from reaching the D-region at horizontal distances greater than about 700 miles.

10.34 The ionization produced by thermal X-ray and ultraviolet light, which is small at lower levels, becomes significant for nuclear detonations in the 40- to 70-mile altitude range. The X-rays, which carry as much as two-thirds of the explosion energy, have a tenth-value thickness of several miles in the air at these altitudes;[3] hence, the electron densities they produce will be high and will extend out to some distance from the point of burst. Figure 10.29, which shows the calculated electron densities at an altitude of 45 miles, produced from a 1-megaton fission yield explosion at various burst heights, includes the effects of X-rays as well as of initial gamma rays and neutrons. For bursts above 40 miles, the X-rays make the major contribution to the ionization.

10.35 Small amounts of ionization, which have been observed at distances up to 5,000 miles, within seconds of a high-altitude burst, have been attributed to the protons and electrons formed by the natural decay of neutrons (half-life about 13 minutes). The protons and electrons, being charged particles, follow the earth's magnetic field lines (§ 2.126), and produce ionization when they enter the atmosphere. Despite the fact that only a small percentage of the neutrons decay in the very short time they spend in the region of interest, the ionization is sufficient to cause a momentarily measurable effect in the lower ionosphere.

10.36 The ionization caused by delayed gamma and beta radiation is important for bursts in the 40- to 70-mile altitude range. Its intensity and location is determined by the location of the fission debris cloud, and the motion of the cloud for bursts in this altitude range is quite different from that for detonations at lower altitudes. Immediately after the time of burst, the thermal X-rays deposit about half of the total energy of the detonation within a few miles of the burst point. If the energy yield is in the megaton range, this energy will be sufficient to dissociate and ionize essentially all the molecules of oxygen and nitrogen in the air and raise the temperature of the region by several thousand degrees.

10.37 Prior to the burst, the air pressure in this region changes with altitude by an amount just sufficient to balance the force of grav-

[3] Because the thermal X-rays cover a wide range of energies (§ 7.80), they do not have a single tenth-value thickness (see § 10.83).

ity. The sudden increase in the temperature of the air causes a proportional increase in the pressure; hence, the pressure is no longer in balance with the gravitational force. This unbalance of forces causes the fireball to be hurled upward at high velocity, possibly as much as a mile per second. Consequently, the weapon debris reaches altitudes of several hundred miles, which are much higher than those to be expected if the rise were caused by buoyancy forces alone. Since the density of the air is extremely low, the particles will fall rapidly from these heights and within an hour will have reached an altitude of about 85 miles. Further fall will be much slower because of the increasing atmospheric density. The upward motion of the debris carries the radioactive particles into the regions where the gamma radiation has extremely long ranges. Thus, the gamma rays from fission residues will produce widespread ionization, although the electron concentration will be low because of the large volume involved. From a height of 300 miles, for example, the gamma rays will produce appreciable ionization in the D-region as far out as 3,000 miles, which is as far as the curvature of the earth will permit.

10.38 For the beta particles emitted by the radioisotopes in the weapon residues, a new situation arises for detonations at high altitudes. Because they carry an electrical charge, these particles follow a spiral path along the earth's magnetic field lines. As the radioactive debris from the burst rises and spreads, the beta particles will travel along the earth's magnetic field lines, about half moving toward the conjugate point in one hemisphere and the other half toward the corresponding point in the other hemisphere (§ 2.127). The particles will travel freely along the field lines at high altitudes, but will suffer collisions with atoms and molecules when they reach the denser air of lower altitudes. At about the D-region (45 miles altitude), the beta particles encounter air at a sufficient density to permit their absorption with accompanying ionization. There will thus be produced two (conjugate) volumes of ionization, one in each hemisphere, where the earth's magnetic field lines passing through the radioactive cloud encounter the D-region (see Fig. 2.127). Each of the volumes will be of roughly the same extent as the cloud and its effective vertical thickness will be about 10 miles, centered at an altitude of 45 miles. The electron density in each ionization volume will be approximately half that to be expected if the radioactive cloud were actually present at that particular location.

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Detonations Above 70 Miles Altitude

10.39 If the burst altitude is from 70 miles up to a few hundred miles, still another behavior pattern can be expected. The initial nuclear radiation and thermal ultraviolet and X-rays traveling downward will cause ionization over a large extent of the D-region, in the manner described above. The radiations going upward, however, will not encounter enough air molecules (or atoms) to be absorbed and most will escape the earth's atmosphere completely. Some widespread ionization of low intensity will be caused, however, by neutrons which decay in the earth's magnetic field, as described in § 10.35.

10.40 The effect of the residual beta and gamma radiation will be determined, as in other cases, by the location of the radioactive debris. The motion of these residues is difficult to predict exactly, but a qualitative picture can be presented. Immediately after the explosion, the weapon debris travels radially outward from the burst point at high velocity, most of the material consisting of fission product (and other) ions and free electrons because of the very high temperatures. At the lower altitudes, the radial motion is quickly stopped by the surrounding atmosphere and the ions and electrons soon re-combine to form neutral atoms. But at the extreme altitudes under consideration, the air density is too low, i.e., collisions between debris and ambient air atoms are too infrequent, to cause any appreciable deceleration of the outward motion of the radioactive particles. However, since the material consists largely of free ions and electrons, i.e., a plasma, the earth's magnetic field plays a significant part in stopping the radial expansion.

10.41 As stated earlier (§ 10.11), a plasma in a magnetic field always tends to exclude the field lines from its interior. Hence, when the weapon debris expands it will cause the earth's field lines to be "stretched" in such a way that they remain outside the conducting volume. This stretching of the lines of force requires that work be done on the field by the expanding debris and the expansion stops when the pressure has decreased to such a point that it is equal to the magnetic pressure (or energy density) of the field. For a 1-megaton fission explosion it is estimated that this would occur at a radius of 600 miles, whereas for a 1-kiloton weapon the radius would be 60 miles.

10.42 If the burst point is not too high, the weapon residues in moving downward will reach a region of appreciable air density, at an altitude of about 85 miles, before the earth's magnetic field halts the expansion; part of the debris will then be stopped and neutralized.

Because of the heating of the air by the thermal X-rays (§ 2.100), the radioactive material will probably be carried upward a short distance by the rising heated air. But it will settle again to an altitude of about 85 miles and be deposited in a circular layer, the radius of which is determined by the fission yield and altitude of the burst. This sheet will irradiate the D-region, the gamma rays producing widespread ionization of low intensity and the beta particles two regions of more intense ionization at locations on the magnetic field lines passing through the radioactive layer (§ 10.38).

10.43 The behavior of that part of the weapon debris which has been stopped by the magnetic field is somewhat uncertain. The distorted magnetic field will begin to recover and, in returning to their normal position, the field lines will probably cause turbulence and will tend to mix ambient air into the debris. Part of the debris will become electrically neutral, by recombination of the ions and electrons, and will no longer be affected by the magnetic field, so that it escapes from the region of confinement; the remainder, which is still charged, will be recompressed. Neutral particles of radioactive debris with sufficient energy and proper direction of motion will escape from the earth's gravitational field. The others will eventually settle to an altitude of about 85 miles and irradiate the D-region with the residual beta and gamma radiation, as described earlier.

10.44 The part of the debris which retains its charge for a longer time, and is confined by the magnetic field, will be in a position to release beta particles in locations and directions suitable for trapping in the earth's magnetic field. These particles, traveling back and forth, as described in § 2.129, and drifting eastward in longitude around the earth, will, within a few hours, spread to form a shell of high-energy beta particles, i.e., electrons, completely around the earth. In the ARGUS experiments, in which the bursts occurred at altitudes of about 300 miles (§ 2.54), well-defined shells, about 60 miles in thickness, were established and remained in place with measurable electron densities for many days. This has become known as the "Argus effect."

Time History of Ionization

10.45 After the ionization in the D-region has increased as the result of a nuclear detonation, the electron density will decay toward the normal value by electron-ion recombination and by electron-neutral particle attachment. If the electron density in the D-region exceeds about 10^6 electrons per cubic centimeter, recombination will

be the dominant process for electron removal both day and night; but if the density is below this value, recombination will predominate in the daytime and attachment at night (§ 10.85 *et seq.*).

10.46 The times required for various electron densities in the D-region to be decreased by a factor of 10 have been calculated and the results are summarized in Table 10.46. The significance of these times is as follows: after 1 second, day or night, all electron densities

TABLE 10.46

CALCULATED RECOVERY TIMES IN D-REGION OF IONOSPHERE

Electron Density (*electrons/cm³*)	*Time for density to decrease by factor of 10*	
	Day (*sec*)	*Night* (*sec*)
10^8 or greater decreased to 10^7	less than 1	less than 1
10^7	10	10
10^6	100	15
10^5	1, 000	15
10^4	10, 000	15

of 10^8 or more will have decreased to 10^7; densities of 10^7 or less will remain essentially unchanged. At 10 seconds later, day or night, the density of 10^7 will have dropped to 10^6, but densities of 10^6 or less will not be appreciably affected. Below a density of about 10^6, the recovery times for day and night are different; during the day, it takes 100 seconds for the electron density to decrease from 10^6 to 10^5, whereas at night the same change requires only 15 seconds. Densities below 10^5 will decrease relatively slowly in the daytime. Since the normal electron density in the D-region is 10^3 in the daytime and almost zero at night, the data in Table 10.46 show that it would take about 3 hours in the day and about 100 seconds at night for this region to recover completely from a sudden increase in the electron density.

10.47 By using the recovery times in Table 10.46 in connection with the curves in Fig. 10.29, it is possible to determine the time history of the ionization produced by the initial nuclear radiation and the thermal radiation from a 1-megaton fission explosion taking place at various altitudes. However, because of simplifications made in the calculations, the results, at best, represent orders of magnitude only. Furthermore, in regions where the ionosphere has been severely disturbed by the nuclear burst, electron densities may remain above 10^7 electrons per cubic centimeter for much longer than the 1 second indicated in Table 10.46.

10.48 The density of electrons produced by the residual beta and gamma radiations decreases at a rate which is somewhat more difficult

to estimate, because the ionization continues over an extended period of time. However, by combining the rates of removal of electrons by recombination and attachment with the rate of decay of the activity of the weapon residues, the results in Figs. 10.48 a and b have been obtained; they refer to 1-megaton fission detonations at altitude ranges of 10 to 40 miles and 40 to 70 miles, respectively. Two quantities are displayed on each figure: the radius to which the debris has expanded (which determines the region in which enhanced electron concentrations occur), and the associated D-region electron densities.

10.49 It is seen, for example, that at 1 hour after a 1-megaton burst in the 10- to 40-mile altitude range, an electron density of about 10^6 will extend over a region of radius 100 miles around the burst point, day or night. At 3 hours after the explosion, a density of 2×10^5 will be found out to a radius of 300 miles in the daytime, but at night the electron density out to this distance would be about 3×10^4 electrons per cubic centimeter.

EFFECTS ON RADIO AND RADAR SIGNALS

INTRODUCTION

10.50 The effects on radio communications systems of the atmospheric ionization produced by nuclear explosions at various altitudes depend on the type of system and in the particular manner in which the ionosphere is involved in transmitting the signals. The latter is determined, in turn, by the operating frequency of the system. It is convenient, therefore, to divide the discussion into sections corresponding to the conventional division of the communications spectrum into various decade frequency ranges. These ranges, with associated frequencies and wavelengths, are enumerated in Table 10.50.

TABLE 10.50

COMMUNICATIONS SPECTRUM

Name of Range	*Frequency Range**	*Wavelength Range*
Veiy-Low-Frequency (VLF)	3–30 kc	10^7–10^6 cm.
Low-Frequency (LF)	30–300 kc	10^6–10^5 cm.
Medium-Frequency (MF)	300 kc–3 Mc	10^5–10^4 cm.
High-Frequency (HF)	3–30 Mc	10^4–10^3 cm.
Very-High-Frequency (VHF)	30–300 Mc	10^3–10^2 cm.
Ultra-High-Frequency (UHF)	300 Mc–3 kMc	10^2–10 cm.

*The abbreviations kc, Mc and kMc refer to kilocycles (10^3 cycles/sec), megacycles (10^6 cycles/sec), and kilomegacycles (10^9 cycles/sec), respectively.

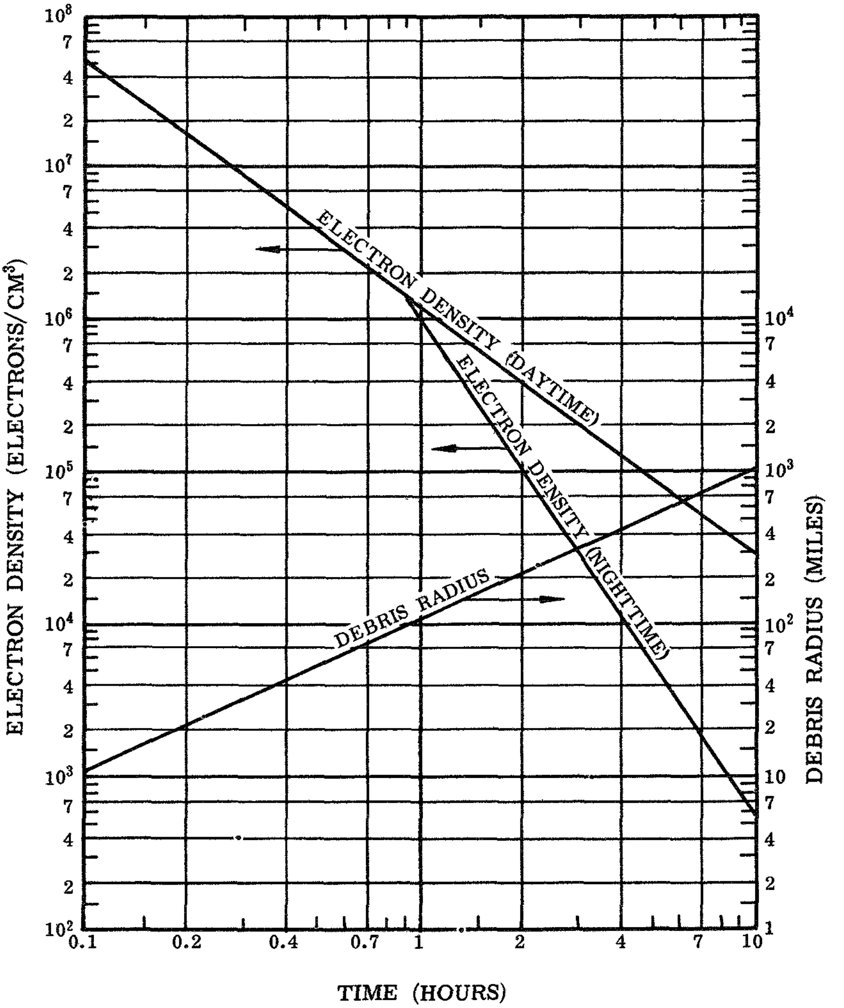

Figure 10.48a. Radius of debris expansion and corresponding D-region electron density as functions of time for a 1-megaton fission detonation in the altitude range of 10 to 40 miles.

Radar systems, which normally employ the frequency range of VHF or higher, are treated separately in § 10.64 *et seq.*

VERY-LOW-FREQUENCY RANGE

10.51 Signals in the VLF range are transmitted by reflection

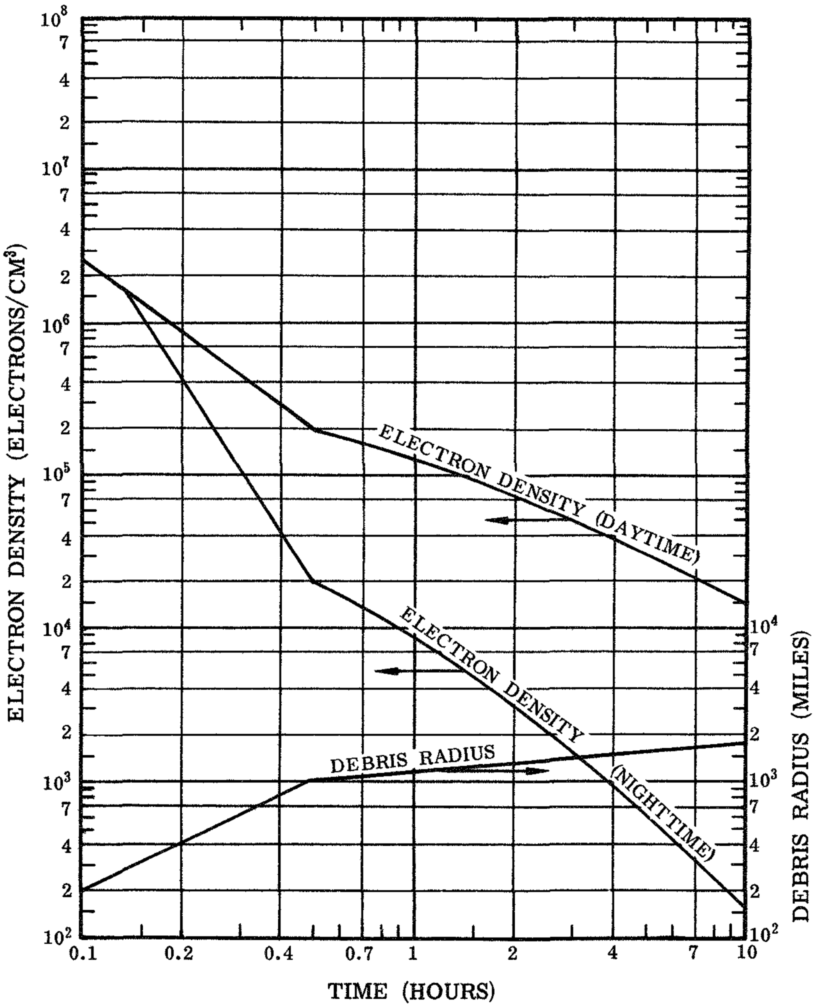

Figure 10.48b. Radius of debris expansion and corresponding D-region electron density as functions of time for a 1-megaton fission detonation in the altitude range of 40 to 70 miles.

between the surface of the earth and the extreme lower boundary of the ionosphere. At these frequencies, signals are reflected by such a slight change in electron density that they do not ordinarily penetrate into the ionosphere past the point where the electron density reaches 10^3 electrons per cubic centimeter. The wave may be regarded as traveling down a duct (or guide) whose boundaries are the earth and that level in the atmosphere at which the electron density is about

10^3 per cubic centimeter. Communication over distances of thousands of miles is possible by this mode.

10.52 Since the signal does not penetrate appreciably into the ionosphere, the additional ionization produced by a nuclear detonation does not cause any serious amount of attenuation. However, the actual distance the signal will travel between transmitter and receiver depends on the height at which the signal is reflected. If the electron density is rapidly increased, the waves will be reflected from a lower altitude and will travel a shorter total distance between transmitter and receiver; hence, the wave will arrive with a shift in phase. The most noticeable effect of a nuclear explosion on a VLF system will thus be a sudden phase shift of the signal at the time the ionosphere is disturbed. This will be followed by gradual recovery as the ionosphere returns to its normal state. Long-range gamma ray and neutron-decay beta ionization may alter VLF propagation conditions at very large distances from the detonation. In fact, after the TEAK and ORANGE high-altitude shots described in Chapter II, the 18.6-kilocycle signal transmitted from the Naval Radio Station at Seattle, Washington, to Cambridge, Massachusetts, suffered an abrupt 40° phase shift. The entire path was at least 3,000 miles from the burst point.

Low- and Medium-Frequency Ranges

10.53 For communications systems operating in the LF and MF regions of the spectrum, a different mode of propagation is normally utilized. Although there is a sky-wave mode, in which the signal is reflected repeatedly by the ionosphere and the ground, it is not normally relied upon for communication because of strong absorption. In the ground-wave mode, the signal is transmitted along the surface of the earth; it tends to bend and follow the curvature of the earth, particularly in regions where the surface is a good conductor of electricity. With reasonable amounts of transmitter power, it is possible to use this method for communication over distances of a few hundred miles. Thus, a high-altitude nuclear burst which changes the conditions in the ionosphere might have drastic effects on the sky-wave transmission but would not be expected to have any appreciable influence on the normally used ground-wave mode, in the LF and MF ranges of the radio spectrum.

The High-Frequency Range

10.54 The HF band is used extensively for long-range communications; the frequencies are high enough to accept information at a rapid rate and yet are sufficiently low to be turned back by the ionosphere. The signals are thus propagated from transmitter to receiver 500 to 5,000 miles away by successive reflections from the ionosphere and the surface of the earth. Each reflection results in some energy loss and so satisfactory operation can be achieved only if there are no more than three reflections from the ionosphere. Frequencies toward the lower end of the range, i.e., around 5 megacycles, are reflected by an electron density of 10^5 electrons per cubic centimeter, which is typical of the E-region, whereas the higher frequencies, e.g., about 20 megacycles, are reflected by the densities of 10^6 electrons per cubic centimeter normally found in the F-region of the ionosphere.

10.55 There are two main ways in which a HF system can be affected by the ionization produced by a nuclear explosion. First, if the signal passes through the D-region at a point where sufficient ionization is present, severe attenuation can result (§ 10.97) and communication will be interrupted. A density of about 10^3 electrons per cubic centimeter in this region is usually sufficient to affect transmission of the lower frequencies of the HF band, whereas about 10^4 electrons per cubic centimeter will interfere with the higher frequency end. From the results given earlier, it can be concluded that for bursts at altitudes below 10 miles no serious interference with HF communications is to be expected. For megaton-range detonations above 10 miles, it is seen from Fig. 10.29 that the initial nuclear radiation and thermal X-rays are sufficient to cause instantaneous disruption of HF signals passing sufficiently close to the burst point. For example, for a megaton burst at a height of 50 miles in the daytime, the effect would be felt out to distances of 600 miles. According to the data in Table 10.46, recovery from this effect would require from about 1,000 seconds (17 minutes) to roughly 10,000 seconds (3 hours), according to the frequency.

10.56 In addition to the initial radiations, the ionization due to the delayed nuclear radiation must be considered. It follows from Fig. 10.48a that a signal passing 500 miles from a megaton burst in the altitude range from 10 to 40 miles will be disrupted by radiation from the debris cloud 5 hours after the burst in the daytime and will not recover until several hours later. For a burst at an altitude of 40 to 70 miles, Fig. 10.48b indicates that a signal 500 miles distant will be affected within 15 minutes and will not recover for 10 hours

or more. At night, the electron density would drop below 10^4 electrons per cubic centimeter in 1 hour and below 10^3 in 4 hours, so that recovery would be expected in 1 to 4 hours. Comparison of Figs. 10.48 a and b shows that, as far as the delayed nuclear radiation is concerned, bursts at higher altitudes influence larger areas but the effects are of shorter duration. It should be remembered, too, that for bursts at 40 to 70 miles altitude there are two similar "blackout" regions due to beta particles, one in each hemisphere (§ 10.38).

10.57 In addition to those specifically considered above, there are other factors which in all cases can affect the duration of HF signal interruptions. Some examples of these other factors are: (1) communication circuit characteristics, e.g., power margin, (2) ionization produced by gamma rays from the weapon residues, (3) ionization at altitudes other than the D-region, and (4) miscellaneous aspects of propagation, e.g., signal refraction by electron density variations. Although some of these factors are important, so that predictions which ignore their influence are not accurate, it is probable that the general nature of the effects, at least, is in accord with the foregoing description.

10.58 The second and quite different manner in which HF communications may be affected by a nuclear explosion is the disturbance of the ionosphere by hydrodynamic motions. If the ionosphere is disturbed in any manner in the vicinity of one of the control points of an HF circuit, i.e., one of the locations in the ionosphere where the signal is reflected, disruption of communications over that circuit may be anticipated. For burst altitudes above 40 miles such disturbances can be expected to occur, despite the low atmospheric density. Just as for lower altitude bursts, a shock wave will be formed and transmitted radially in all directions from the burst. When that part of the shock front traveling upward and outward reaches altitudes corresponding to the E- and lower F-regions, it will encounter air of such low density that further propagation can occur with very little loss of energy. Thus, although the shock contains only a small fraction of the explosion energy, it will move outward for very long distances—possibly thousands of miles for a megaton burst—carrying with it most of the atmosphere in the upper E- and lower F-regions. The disturbance travels at about 2,000 miles per hour and after its passage the ionosphere will require from one to several hours to recover. If a HF system has one of its control points within 1,000 miles of a megaton burst in the altitude range from 40 to 70 miles, it will probably be disrupted for a period of an hour or more. Many instances of the interruption of HF propagation were observed in connection

with the TEAK and ORANGE shots. For example, a 15-megacycle signal from WWVH, Hawaii, which was being received at Hiraiso, Japan, was lost for several hours following the burst. The signal path in this case passed within about 600 miles of the point of detonation.

Very-High-Frequency Range

10.59 Signals in the VHF range are sufficiently penetrating to be able to pierce the normal ionosphere and escape from earth completely. This frequency range is primarily used for line-of-sight communications over short distances, e.g., commercial television channels and FM radio, but long-range communication is possible by making use of the small amount of transmitted energy that is scattered back to earth by patches of unusually intense ionization. The so-called "forward propagation ionospheric scatter" systems are inefficient, since only a minute fraction of the energy of the transmitter reaches the receiver, but they are nevertheless employed, to some extent, because of the demands on the electromagnetic spectrum.

10.60 The ionization from a nuclear burst affects ionospheric scatter systems in two ways. The enhanced electron density will tend to increase the fraction of the signal that is scattered and will thus improve reception; on the other hand, it will also absorb more of the signal energy and so tend to weaken it. No evidence is available from weapons tests concerning the relationship between these two effects, but theoretical studies and observations made during natural disturbances of the ionosphere indicate that they will roughly counterbalance one another, so that no net change is to be expected.

10.61 A side effect of the increased ionization in the ionosphere may be important for long-range scatter links. Transmitter and receiver are usually 500 to 1,500 miles apart and scattering occurs from ionized regions at heights of about 60 miles. If electron densities in the D-region reach 10^4 electrons per cubic centimeter, scattering will take place at altitudes of some 40 miles. Because of the curvature of the earth, a signal which reaches an altitude of only 40 miles will return to the surface at a maximum distance of 1,200 miles from the transmitter. Hence, communication over longer distances than this may be cut off for the time during which the D-region has a density of 10^4 electrons per cubic centimeter or more. The distances and times for which this density is exceeded may be obtained from Figs. 10.48 a and b.

ULTRA-HIGH-FREQUENCY RANGE AND ABOVE

10.62 Frequencies in the UHF range and above are little affected by the electron densities normally occurring in the ionosphere. They are used for point-to-point (line-of-sight) communications between ground stations, aircraft stations, and between ground stations and satellites. The wavelength at a frequency of 300 megacycles is 1 meter, and signals of such wavelengths are scattered in the atmosphere, possibly because of variations in water vapor content, the presence of particulate matter, or other properties of the air. Use is made of this scattering, in the so-called "tropospheric scatter" systems, for communication over ranges up to 600 miles around the curve of the earth. Such systems, as well as those involving line-of-sight stations below the ionosphere, are essentially unaffected by nuclear bursts which disturb the ionosphere. They might be disrupted for a short time by a surface or low-altitude burst directly between the stations, but the effect would probably last no more than seconds.

10.63 For line-of-sight communication with satellites, the situation is different because the UHF signal does have to penetrate the ionosphere. The amount of attenuation caused by free electrons is less than for frequencies in the HF band. Consequently, it is expected that communications will not be greatly affected, provided the electron density does not exceed 10^7 electrons per cubic centimeter. It is seen from Table 10.46 that such high densities will not exist for more than about 1 second, except in the immediate vicinity of the burst where the atmosphere is disturbed. Nuclear blackout of ground-to-satellite communication will not be so serious as for some of the other systems which have been considered.

EFFECTS ON RADAR

10.64 Radar systems are similar to radio communications systems in the respect that a transmitter and receiver of electromagnetic waves are used. However, in radar the receiver is located near the transmitter and may use the same antenna, which may be highly directional. The transmitted signal, consisting of a series of pulses, is in part reflected back to the receiver, like an echo, by objects in the path of the pulsed beam. From the direction of the antenna and the travel time of the signal, information can be obtained concerning the location and movement of the source of the echo. Frequencies normally employed in this connection are in the VHF range and above. As was seen in the discussion of effects on communica-

tion, there is little effect on signals of these frequencies so long as both the radar and the target are below the ionosphere.

10.65 If the signal must pass through the ionosphere, however, the interference from nuclear detonations becomes important. Radar signals traversing the ionosphere will, like radio signals, be subject to attenuation. Although any additional attenuation is undesirable, the amount which can be tolerated varies widely with the type of radar and the purpose of the system. In search radars, for example, where it is desired to detect each target at the greatest possible range, i.e., just as soon as the target return becomes observable against the background noise, even the smallest additional signal loss results directly in shortening of the range at which a given target can be detected. A tracking or guidance radar in a weapon system, on the other hand, usually takes over its target, well inside its maximum detection range, from another (search) radar which has already detected and tracked the object. In this case the signal may be attenuated to a much greater degree before the radar loses its ability to acquire or track. For this reason, subsequent discussion will be limited to estimating the amounts of attenuation to be expected without making any attempt to assess their significance.

10.66. Signal attenuation is expressed in terms of decibels (§ 10.76), where 1 decibel corresponds to a decrease in strength to roughly 0.8 of the original value; 2 decibels to about $(0.8)^2$, i.e., 0.64; 3 decibels to $(0.8)^3$, i.e., 0.51; 10 decibels to exactly 0.1; 20 decibels to 0.01; 30 decibels to 0.001 of the original value, and so on. For a radar system, a 12-decibel drop in power would result in a decrease in effective range by a factor of two.

10.67. As mentioned in § 10.25, maximum attenuation effects occur mainly within a 10-mile range centered around an altitude of about 45 miles. In this region, which coincides with the D-region of the normal ionosphere, an electron density of 1 electron per cubic centimeter will cause a 10-megacycle signal to suffer an attenuation of about 4×10^{-5} decibel per mile of travel. For other electron densities and for higher signal frequencies, the attenuation is directly proportional to the electron density and inversely proportional to the square of the signal frequency. For frequencies below 10 megacycles, the frequency dependence is more complicated. The electron density information given in Fig. 10.29 and Figs. 10.48 a and b can thus be used to calculate attenuation effects for radar systems for frequencies of 10 megacycles or more.

10.68. As an example of the calculation of attenuation for a radar system, consider a 100-megacycle radar tracking a target above the

D-region 1.5 hours after a 1-megaton daytime explosion in the 10- to 40-mile altitude range. According to Fig. 10.48a, at this time an electron density of about 5×10^5 per cubic centimeter exists in the D-region within a 150-mile radius of the burst point. If the radar beam passes through this region, attenuation will occur. For a 10 megacycle signal and 1 electron per cubic centimeter, the attenuation would be 4×10^{-5} decibel per mile. For a frequency 10 times as great, this must be divided by 10^2. For an electron density of 5×10^5, and a frequency of 100 megacycles, therefore, the attenuation is $4 \times 10^{-5} \times 5 \times 10^5 / 10^2 = 0.2$ decibel per mile. Since the region is 10 miles thick, a radar signal traversing the region and returning, in a vertical direction, will travel a distance of 20 miles through the attenuating region, so that the total attenuation for a signal traveling in the vertical direction would be $20 \times 0.2 = 4$ decibels.

10.69. If the signal makes an angle θ with the vertical, the distance traveled through the attenuating layer will be increased by a factor of $1/\cos \theta$, i.e., $\sec \theta$, and the attenuation in decibels is obtained upon multiplying the value for the vertical signal by this factor. For example, if the radar beam is at 80° to the vertical direction, the correction factor is $1/\cos 80°$, i.e., roughly 6. Hence, the total attenuation would be $6 \times 4 = 24$ decibels.

10.70. In many instances, refraction of a radar beam, as a result of variation in electron density, can be as important as attenuation. Figure 10.70 shows the amount of bending (or refraction) which will occur when a 100-megacycle radar beam encounters an electron density *change* of 10^6 electrons per cubic centimeter. The amount of bending is directly proportional to the electron density change and inversely proportional to the square of the signal frequency, so the figure may be used for other electron density changes and signal frequencies. It applies, however, only for frequencies greater than 10 megacycles, and angles of refraction less than 5°. Since the electron density below the D-region is essentially zero, Fig. 10.70 will provide a rough estimate of the amount of bending suffered by a radar beam entering the D-region from below. For example, if the D-region electron density were 10^6, and if a 100-megacycle beam were incident at an angle of 70°, i.e., 70° angle with the vertical, the bending would be about 0.8°.

10.71. For some large angles of incidence, θ, reflection will occur and the radar signal will be turned back without passing through the attenuating region. The values of the angle θ for various electron densities and signal frequencies are given in Fig. 10.71. It can be used in conjunction with Fig. 10.29 and Figs. 10.48 a and b to deter-

mine whether a radar beam will suffer total reflection under particular circumstances associated with a 1-megaton, high-altitude explosion.

10.72. Other disruptions of radar signals may occur as a result of ionization from a nuclear detonation. The ionization produced tends to become nonuniform and to align itself in columns of differing density along the direction of the earth's magnetic field. These irregu-

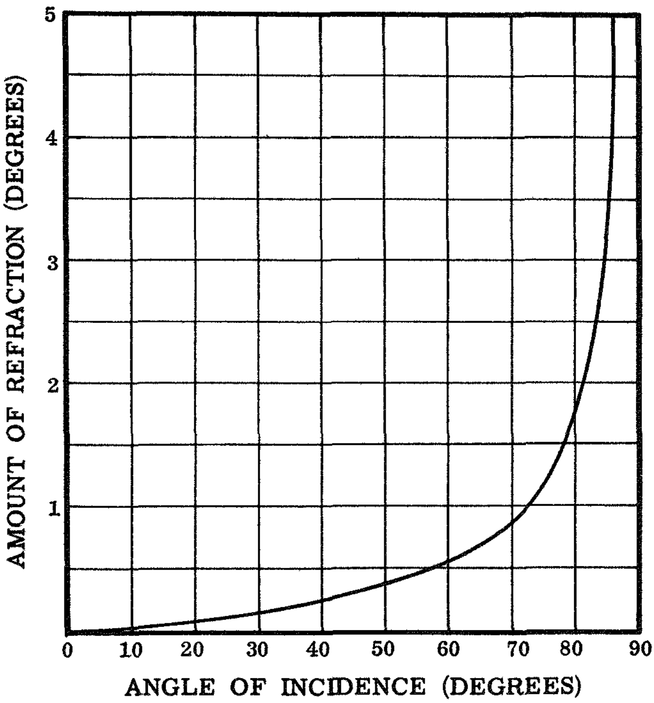

Figure 10.70. Refraction of 100-megacycle radar beam by an electron density change of 10^6 electrons/cm^3 as function of angle of incidence.

larities can disrupt the radar beam causing an effect similar to the "twinkling" of stars, and "clutter" or false echoes from ionized patches. However, not enough is known of these phenomena to permit a quantitative description.

Effects of Surface and Subsurface Bursts

10.73 It has already been seen that bursts at altitudes below 10 miles do not produce sufficient quantities of persistent ionization to

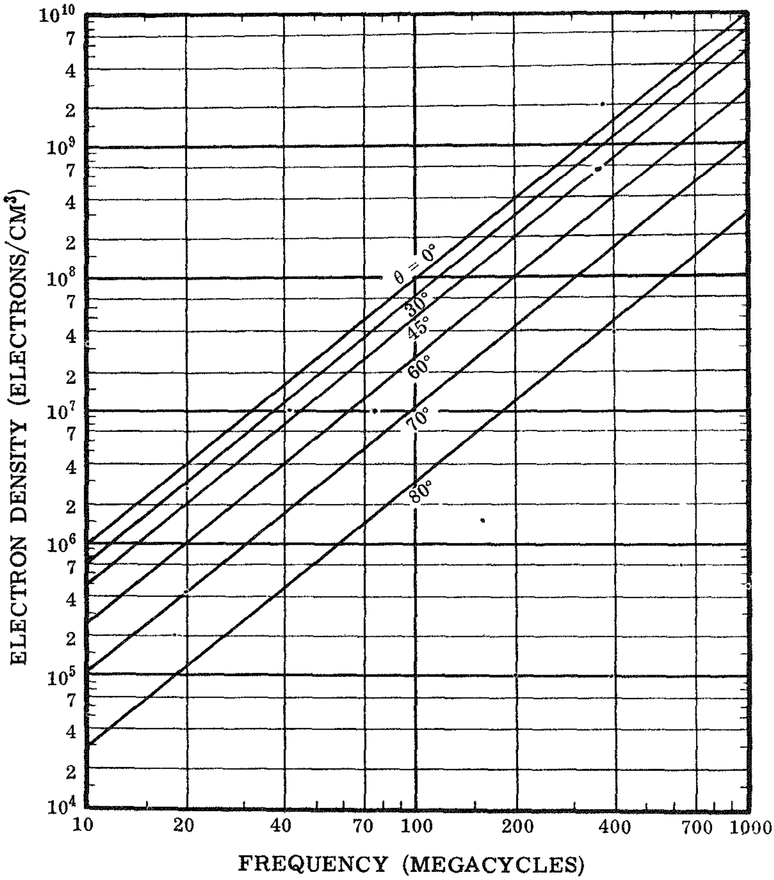

Figure 10.71. Angles of incidence for reflection of radar beam as function of frequency and electron density.

cause serious effects on radio or radar systems. For surface and subsurface (land or water) bursts, particulate matter or water introduced into the atmosphere by the nuclear explosion can cause some disturbance of radio wave propagation. Particles of dust, debris, water droplets, or ice crystals in the cloud formed by a detonation can act as reflectors for some electromagnetic signals. A particle is an efficient reflector of an electromagnetic wave if its size is somewhat comparable to the wavelength. Most of the particles are quite small (1 mm or less in diameter), whereas the shortest wavelengths for radars in general use (X and K bands) are 1 to 6 centimeters. Nevertheless, there are sufficient numbers of particles of the appropriate

size present in the early stages after an explosion to produce echoes in X- or K-band radars. This condition may last for minutes or hours, depending on the weapon yield, the nature of the particles picked up by the burst, and the rate at which the cloud spreads in the atmosphere. Because of the small size of the particles, electromagnetic radiation of longer wavelengths, associated with lower frequency radar or with radio communications systems, will not be affected.

TECHNICAL ASPECTS OF RADIO AND RADAR EFFECTS[4]

Density of Atmosphere and Altitude

10.74 The density of the atmosphere from the surface of the earth up to an altitude of about 80 miles can be represented with fair accuracy by the formula

$$\rho \approx \rho_0 e^{-z/4.3}, \tag{10.74.1}$$

where ρ_0 is the sea-level density and ρ is the value, in the same units, at an altitude of z miles. For higher altitudes, the density decreases somewhat more slowly than is implied by equation (10.74.1), but since altitudes below 80 miles are of primary interest for the present purpose, the simple exponential relationship will be employed.

10.75 It follows from equation (10.74.1) that the air density decreases by a factor of e, i.e., 2.72, for every 4.3 miles increase in altitude. By writing the expression in the alternative form

$$\rho \approx \rho_0 10^{-z/10},$$

it is seen that the density changes by a factor of roughly 10 for every 10 miles of altitude. Thus, any property of the atmosphere which is proportional to the air density changes by an order of magnitude for a change of 10 miles in altitude.

Signal Attenuation

10.76 The decibel, which is used to express electromagnetic (and other) signal attenuation, is defined by

$$\text{Attenuation in decibels} = 10 \log \left(\frac{P_{\text{in}}}{P_{\text{out}}}\right),$$

[4] The remaining sections of this chapter may be omitted without loss of continuity.

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where P_{in} is the signal power before attenuation and P_{out} that after attenuation. When an electromagnetic signal travels through an ionized medium, the attenuation A, expressed in decibels per mile of path, is

$$A=\frac{2.9\times 10^4 N\nu}{\omega^2+\nu^2}, \qquad (10.76.1)$$

where N is the electron density, i.e., number of electrons per cubic centimeter, ν is the number of collisions per second which an electron makes with ions or atoms, and ω is the (angular) frequency of the wave (in radians per second). It follows from equation (10.76.1) that if the collision frequency ν is small then, for a given wave frequency, A will be small because of the ν in the numerator. On the other hand, if ν is very large, A will again be small because of the ν^2 in the denominator. Thus, the attenuation passes through a maximum for a particular value of the collision frequency.

10.77 Since the collision frequency is proportional to the density of the air, it will decrease exponentially with altitude. It is to be expected, therefore, that the values of ν for which attenuation of signals is important would occur only within a relatively narrow altitude region. More complete theoretical studies show that the attenuation occurs mainly within a 10-mile range centered about an altitude of about 45 miles. In addition, it has been found that the greatest electron densities accompanying nuclear detonations generally occur at approximately this same altitude. Hence, by confining attention to the situation in the neighborhood of a 45-mile altitude, it is possible to avoid complexities and yet present a reasonably accurate picture of the effects of the burst on electromagnetic signals.

Electron Densities From Initial Radiations

10.78 An estimate of the electron density produced at a given distance from a nuclear burst by gamma radiation can be obtained by utilizing a slight modification of equation (8.98.1); as before, the weapon is treated as a point source. Let W kilotons be the total energy yield of the explosion and k the fraction which appears as initial gamma radiation; then the gamma-ray energy, E kilotons per unit area, arriving at a given point at a distance (slant range) D from the detonation is

$$E=\frac{kW}{4\pi R^2}\, e^{-\bar{\mu}D}, \qquad (10.78.1)$$

where $\bar{\mu}$ is an effective (or average) linear absorption coefficient along the path of the radiation.

10.79 The average coefficient, $\bar{\mu}$, may be expressed in terms of the linear absorption coefficient, μ, at any point distant D' from the explosion by

$$\bar{\mu}=\frac{1}{D}\int_0^D \mu dD'. \tag{10.79.1}$$

The mass absorption coefficient, μ_m, is equal to μ divided by the density (§ 8.79); that is,

$$\mu=\mu_m\rho.$$

Upon substituting this result, together with equation (10.74.1), into equation (10.79.1), it is found that

$$\bar{\mu}=\frac{\mu_m\rho_0}{D}\int_0^D e^{-z/4.3}\, dD'. \tag{10.79.2}$$

If the detonation occurs at an altitude H_0, and H is the altitude of the observation point at a slant distance D from the explosion, where H may be either above or below H_0, then changing the variable in equation (10.79.2) leads to

$$\bar{\mu}=\frac{\mu_m\rho_0}{H-H_0}\int_{H_0}^H e^{-z/4.3}\, dz.$$

Replacing $\mu_m\rho_0$ by its equivalent, μ_0, the linear absorption coefficient of air at sea level, and performing the integration, the result is

$$\bar{\mu}=\frac{4.3\mu_0}{H-H_0}\,(e^{-H_0/4.3}-e^{-H/4.3}). \tag{10.79.3}$$

10.80 The gamma-ray energy absorbed per unit volume of air at the point under consideration, i.e., altitude H, is equal to $E\mu$, where E is given by equation (10.78.1) and μ is the absorption coefficient [5] at altitude H. As seen above, μ may be written as $\mu_m\rho$, and ρ may be expressed in terms of ρ_0 by equation (10.74.1); hence,

$$\begin{aligned}\text{Energy absorbed per unit volume} &= E\mu_m\rho_0 e^{-H/4.3}\\ &= E\mu_0 e^{-H/4.3}.\end{aligned}$$

[5] Since all the gamma-ray photons are ultimately absorbed in the atmosphere, μ is employed here instead of the conventional energy absorption coefficient.

Since 1 kiloton of explosion energy is equivalent to 4.2×10^{19} ergs (Table 1.41) and 1 electron volt is 1.6×10^{-12} erg (§ 1.39), it follows that 1 kiloton is equal to 2.6×10^{31} electron volts. It requires 34 electron volts to produce one ion pair, and hence one electron, in air; consequently, the number of free electrons, N, produced per unit volume is

$$N=\frac{2.6\times10^{31}}{34}E\mu_0 e^{-H/4.3},$$

where E is expressed in kilotons per unit area, i.e., by equation (10.78.1). Upon substituting from equations (10.78.1) and (10.79.3), the result is

$$N=\frac{6.2\times10^{28}\mu_0 kW}{D^2}e^{-(x+H/4.3)}, \qquad (10.80.1)$$

where

$$x=\left[\frac{4.3\mu_0 D}{H-H_0}\left(e^{-H_0/4.3}-e^{-H/4.3}\right)\right].$$

In equation (10.80.1), H and H_0 are in miles, W in kilotons, μ_0 in reciprocal centimeters, and D in centimeters, to give N in electrons per cubic centimeter. It was seen in § 8.100 (footnote) that, for the initial gamma radiations, the relaxation length, λ, which is equivalent to $1/\mu_0$, is about 325 yards for sea-level air density; hence, μ_0 is close to 3.0×10^{-5} reciprocal centimeters. The energy of the initial gamma radiation leaving the exploding weapon is estimated to be about 0.03 percent of the total energy so that k is 3×10^{-4}. Hence, all the information is available to permit the use of equation (10.80.1) for calculating the electron density produced by the initial gamma rays.

10.81 Equation (10.80.1) can also be employed, in principle, to estimate the electron density produced by the neutrons present in the initial radiation. However, the situation is somewhat complicated for various reasons. In the first place, the proportion of the total energy yield which appears as energy of the escaping neutrons varies widely with the nature and design of the weapon. Furthermore, neutrons produce ionization in air as the result of a number of indirect processes, which vary with the altitude. Since the sea-level mean free path for weapon neutrons is not greatly different from that for the initial gamma radiation, and since the ultimate result of the neutron processes is the production of ionization, a very crude estimate of electron density produced by the neutrons in the initial nuclear radiation may be made as follows. From the data in Chapter VIII, it is known that the amount of energy carried by the neutrons leaving

an exploding weapon may range from 1 to 40 times the energy in the initial gamma radiation. For the purpose of making an order-of-magnitude estimate, it is assumed that the electron density produced by both gamma rays and neutrons present in the initial nuclear radiation is equal to 10 times that resulting from the gamma rays alone.

10.82 The electron density produced by the gamma rays can be determined from equation (10.80.1) and the results obtained in this manner were multiplied by 10 to give the data used to plot the curves in Fig. 10.82. These curves give approximate electron densities produced by the initial nuclear radiation at various horizontal distances at a height (H) of 45 miles for a 1-megaton weapon detonated at various altitudes (H_0). The broken cut-off line indicates where the curvature of the earth prevents the nuclear radiations from reaching the 45-mile altitude.[6]

10.83 For altitudes which are sufficiently high for the thermal X-rays to have appreciable mean free paths (or relaxation lengths) the electron densities produced may also be calculated by means of equation (10.80.1). However, since these radiations cover a wide range of frequencies (or wavelengths), there is not a single relaxation length (or absorption coefficient), since the latter varies with energy of the photon in accordance with equation (7.84.1). To make an order-of-magnitude estimate of the ionization produced by thermal X-rays, a round-number temperature of 10^7 degrees Kelvin was assumed for simplicity, as in § 7.84. The radiant power distribution as a function of wavelength (or photon energy) was then obtained from Fig. 7.79. The photons over the whole spectrum were divided into five energy groups, and each group was assigned a separate mean free path in accordance with equation (7.84.1). Then equation (10.80.1) was applied to each individual group and the results added; the value of k was taken to be 0.67, i.e., two-thirds of the explosion energy was assumed to be emitted as the initial thermal radiation capable of producing ionization in air. In this way, the curves in Fig. 10.83 were obtained for the electron densities produced at an altitude of 45 miles by the thermal X-rays from a 1-megaton fission yield explosion.[7]

10.84 The curves in Fig. 10.29 were obtained by addition of the data in Figs. 10.82 and 10.83. Hence, they represent the electron densities that may be expected at an altitude of 45 miles from all

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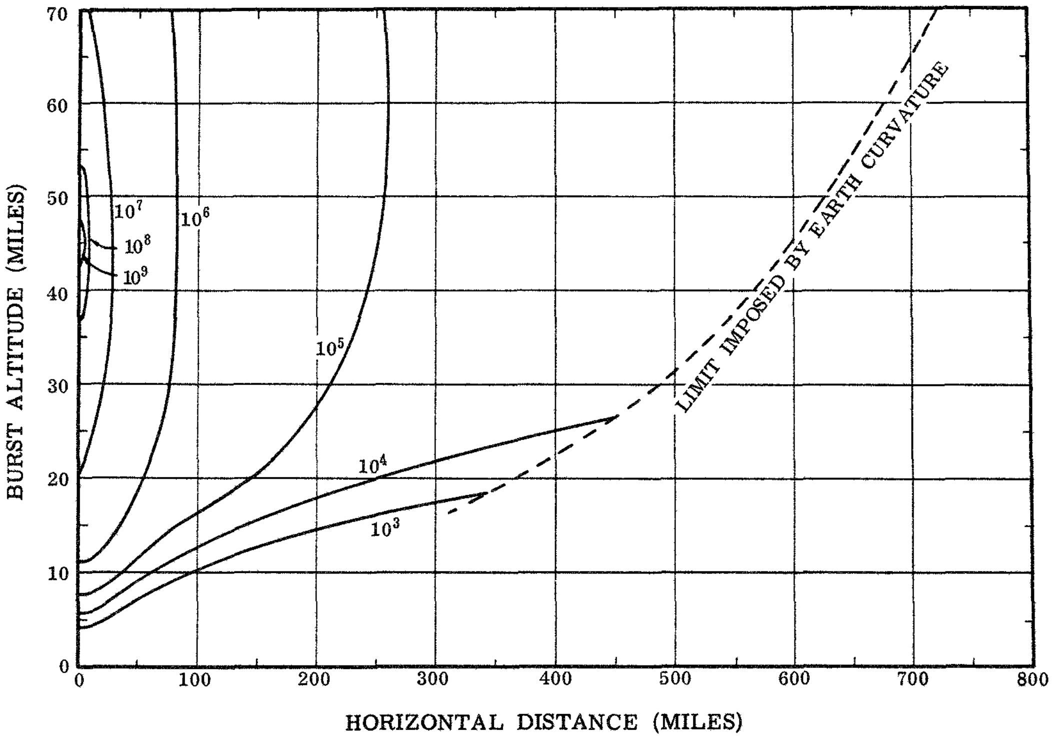
[6] The calculations are based on the so-called "flat earth" model, but with the horizontal distance limited by the earth's curvature. It is assumed that the initial nuclear radiations do not penetrate the atmosphere below an altitude of 15 miles.

[7] The same model was used as for the initial nuclear radiations except that the cut-off due to the earth's curvature was taken at an altitude of 20 miles, rather than 15 miles, because the thermal X-rays are more readily absorbed by the atmosphere.



FIGURF 10.82. Calculated electron densities at an altitude of 45 miles produced by the initial nuclear radiations from a 1-megaton fission yield explosion at various burst heights as a function of horizontal distance.

lisions to cause considerable attenuation of the electromagnetic waves, in the manner described in §10.14.

10.20 In the E-region of the ionosphere (50 to 80 miles altitude), the air density is quite low, about 10^{-5} to 10^{-8} of the sea-level value, and the average lifetime of electrons is even longer than in the D-region. The peak daytime electron density is about 10^5 electrons per cubic centimeter, but most of the ionization, as in the D-region, disappears at night. However, because of the very low density of neutral particles, the frequency of collisions between them and electrons is so small that there is relatively little attenuation of electromagnetic signals.

10.21 Above an altitude of 80 miles is the F-region of the ionosphere. Here the neutral particle density is so low that free electrons have extremely long lifetimes. At an altitude of about 160 miles, the peak daytime density is about 10^6 electrons per cubic centimeter, decreasing to about 10^5 at night. At lower altitudes, the nighttime density is somewhat less than this value. Attenuation of electromagnetic signals in the F-region is small despite the high electron density, because of the very low electron-neutral collision frequency, but refraction effects are important.

10.22 When a radio (or radar) wave travels upward, it commences to be refracted (or bent) when it reaches the D-region, where the first increase in electron density is encountered. As it penetrates into this region, where the electron density increases toward the peak value, more and more bending occurs so that, if the angle of incidence is not too small, the wave may actually be refracted back toward the earth. This process is frequently referred to as "reflection", although it is not the same as true reflection, in which there is no penetration of the ionized layer of air. True (or specular) reflection does occur, to some extent, especially for the lowest radiofrequencies; there will be reflection, as for visible light, when the sine of the angle of incidence is equal to (or exceeds) the refractive index of the ionized region. If the angle of incidence is fairly small, the electromagnetic wave will not be refracted sufficiently in the D-region to be returned to earth, but it will penetrate into the E-region or even into the F-region where the peak electron densities are higher and then be turned back. Normally there is very little reflection in the D-region; electromagnetic waves of higher frequencies, e.g., about 1 megacycle or more, used for communication purposes are generally reflected in the E- and F-regions.

IONIZATION PRODUCED BY NUCLEAR EXPLOSIONS

Introduction

10.23 Both nuclear and thermal radiations from a nuclear explosion can produce ionization in the air, and anywhere from 10 to 75 percent of the total energy yield, depending on the height of burst, may be expended in this respect. Utilizing the value of 34 ev as the amount of energy required to produce one ion pair in air, it is found that if only 10 percent of the energy of a megaton weapon were utilized for this purpose, a total of about 10^{32} free electrons would be formed. This is approximately equal to the number of free electrons in the entire normal ionosphere. Since many communications systems are profoundly affected by, or are even dependent upon, the ionospheric ionization, it is apparent that major consequences to such systems are possible as the result of a nuclear explosion.

10.24 In the subsequent treatment of the manner in which the electron density in the ionosphere can be affected by nuclear detonations, various burst height ranges, associated with different mechanisms, will be considered. It should be understood, however, that these ranges are somewhat arbitrary and are chosen for convenience in bringing out the changes in behavior that occur with burst height. Actually, there are no lines of demarcation between the various altitude ranges; the changes are continuous, but one type of mechanism gradually supersedes another and becomes the dominating one in each of the indicated regions.

10.25 For electromagnetic waves in the radio and radar range, circumstances are such that the maximum attenuation effects occur mainly within a 10-mile range centered around an altitude of about 45 miles. Hence most of the subsequent discussions pertain to this relatively narrow altitude region, which coincides with the D-region of the normal ionosphere.

Detonations Below 10 Miles Altitude

10.26 For nuclear detonations at altitudes below about 10 miles, much of the ionization produced in the surrounding air by the initial gamma radiation and neutrons and also by the thermal X-rays will be contained within a few hundred yards of the fireball. These free electrons will attach themselves almost immediately to neutral particles in the atmosphere, so that they will have a very short lifetime.

Within the fireball, the high temperature, of the order of a million degrees or so, will produce considerable ionization for a small fraction of a second. During this short period the free electron density in the fireball region will be sufficient to cause some attenuation of electromagnetic signals in the immediate vicinity of the burst. This effect will, however, disappear in a matter of seconds.

10.27 As the fireball rises, the residual nuclear radiation, mainly beta particles and gamma rays from the fission products and other weapon debris, will produce ionization in the immediate vicinity. Since the air density is quite appreciable, the free electrons will be rapidly removed by attachment to neutral particles and so their density will remain low. Consequently, unless the radioactive cloud rises to considerable heights, e.g., 20 miles or more, there will be little effect on radiofrequency wave propagation, in spite of the continuous emission of beta particles and gamma rays.

10.28 For explosions with yields in the megaton range, the radioactive cloud may rise to heights of more than 20 miles. The gamma radiation is emitted in all directions and although that going downward is of little consequence, as stated above, the situation is different for the rays traveling upward, into regions of low air density. The tenth-value thickness (§ 8.34) for absorption of the residual gamma radiation at altitudes of over 20 miles is more than 12 miles. Consequently, an appreciable proportion of the gamma rays will reach the D-region of the ionosphere and free electrons produced there will persist for several minutes. The continued emission of gamma radiation from the weapon residues in the radioactive cloud will then result in the build-up of a considerable concentration of electrons. Hence, a large-yield explosion at a fairly low altitude can cause abnormally high electron densities in the D-region that persist for several hours after the burst.

Detonations at 10 to 40 Miles Altitude

10.29 If the burst occurs in the altitude range of roughly 10 to 40 miles, where the air density is low, some of the initial nuclear radiations (gamma ray and neutrons) and, to a minor extent, the thermal X-rays will reach the D-region and cause significant amounts of ionization there. The approximate calculated electron densities at an altitude of 45 miles, where the densities are expected to be maximal (§ 10.77), resulting from a 1-megaton fission yield explosion at various burst heights, are shown in Fig. 10.29 as a function of

horizontal distance.[2] For example, for a 1-megaton burst at a height of 30 miles, the electron density in the D-region (45 mile altitude) is 10^7 electrons per cubic centimeter at a horizontal distance of 40 miles, 10^6 at 80 miles, and so on. The horizontal distance over which the ionization occurs is limited by the curvature of the earth to the portion of the D-region that is in line-of-sight of the explosion, as shown by the broken curve in Fig. 10.29.

10.30 The lifetime of the electrons produced in the D-region is not known with any degree of accuracy, but it will probably be a few minutes (see § 10.46). As the electrons are removed, by attachment to neutral particles or by recombination with ions, more free electrons are produced by the beta particles and gamma rays from the fission products, etc., in the rising fireball. The electron density will depend on the altitude attained by the weapon residues and this will vary with the explosion yield and the height of burst.

10.31 The fission debris cloud from a 1-megaton detonation in the lower atmosphere will attain a height of 20 miles or so; hence, from a burst of the same yield at an altitude of 20 miles, the cloud may be expected to reach a height of about 40 miles above the earth's surface. The air density at this altitude is so low that the tenth-value thickness of the residual gamma rays will be over 2,000 miles, and hence ionization will be produced over a large area extending horizontally a great distance from the radioactive cloud. The beta particles will have a total range of about 20 miles, so that the ionization accompanying their absorption will occur in the vicinity of the cloud. The resulting electron density will depend on the density of the radioactive debris, on the time since the explosion, and on the lifetime of the free electrons. Some estimates of the electron densities are given in § 10.48.

10.32 Outside the cloud, except in that portion of the D-region below it, the electron densities produced by the gamma radiation will be small. However, the gamma rays traveling downward enter a region of somewhat higher air density. They are consequently absorbed within a shorter distance and may produce significant electron densities.

Detonation at 40 to 70 Miles Altitude

10.33 For bursts at altitudes of approximately 40 to 70 miles, the initial gamma rays and neutrons have tenth-value thicknesses

[2] It should be noted that the curves show only the electron densities produced by the nuclear explosion and do not include the ionization caused by sunlight or arising from other natural causes.

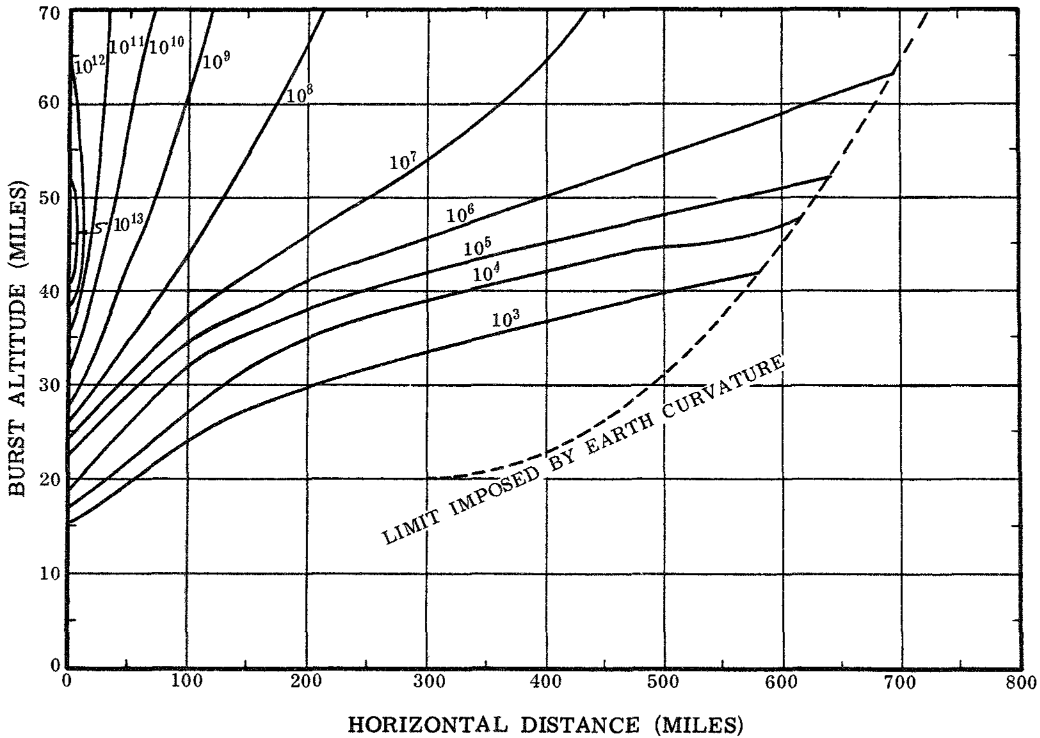


Figure 10.83. Calculated electron densities at an altitude or 45 miles produced by the thermal X-rays from a 1-megaton fission yield explosion at various burst heights as a function of horizontal distance.

the ionizing radiations emitted at the time of the explosion of a 1-megaton weapon at various heights. Comparison of the three figures shows that for burst heights below about 40 miles the ionizing effect of the initial nuclear radiations is predominant, but at higher burst altitudes the thermal X-rays produce essentially all the electrons.

Rate of Disappearance of Free Electrons

10.85 Free electrons are removed either by attachment to neutral atoms or molecules or by recombination with positive ions. In the daytime, recombination is the only significant mechanism because sunlight tends to remove an electron immediately it becomes attached to a neutral particle. The recombination rate is proportional to the densities of both electrons (N) and ions (N_i) so that

$$\text{Recombination rate} = \alpha N N_i, \tag{10.85.1}$$

where α is the proportionality constant, called the "recombination coefficient." The numbers of electrons and positive ions per unit volume are essentially equal, since the region of the atmosphere is electrically neutral as a whole; hence, N_i is equal to N and equation (10.85.1) may be written

$$\text{Recombination rate} = \alpha N^2. \tag{10.85.2}$$

For the normal ionosphere, e.g., at an altitude of about 45 miles, α is approximately 10^{-7} in second per cubic centimeter units, and so the number of recombinations per cubic centimeter per second is given by

$$\text{Recombination rate} = 10^{-7} N^2. \tag{10.85.3}$$

10.86 At night, electron attachment to neutral particles becomes significant. The attachment rate is proportional to the densities of electrons (N) and of neutral particles (N_n) so that

$$\text{Attachment rate} = \beta N N_n,$$

where β is the "attachment coefficient"; for an altitude of 45 miles, β is about 10^{-16} second per cubic centimeter. At this altitude, there are some 1.6×10^{15} neutral particles per cubic centimeter, and so the nighttime attachment rate, expressed as number of attachments per cubic centimeter per second, is

$$\text{Attachment rate} = 10^{-16} \times 1.6 \times 10^{15} N = 0.16 N. \tag{10.86.1}$$

By comparison with equation (10.85.3) it is seen that attachment is the chief mode of electron removal at night if N is less than 1.6×10^6, but recombination is the more important when N exceeds 1.6×10^6 electrons per cubic centimeter. Hence, for electron densities greater than 1.6×10^6, equation (10.85.3) should be used for nighttime as well as daytime.

10.87 If N_0 is the electron density produced by the initial nuclear radiations and thermal X-rays at the instant of the nuclear explosion, and no further ionization occurs, it follows from equation (10.85.3) that the electron density N at a time t seconds later is

$$N = \frac{N_0}{1+10^{-7}N_0 t}. \qquad (10.87.1)$$

Provided no additional ionization occurs, this expression is applicable if N_0 is the density at any arbitrary starting time. If N_0 is very large, e.g., greater than 10^8, then at times of 1 second or later, unity in the denominator of equation (10.87.1) can be neglected, so that

$$N \approx 10^7 t^{-1}.$$

At the end of 1 second, therefore, i.e., when $t=1$, the electron density will have fallen to 10^7 electrons per cubic centimeter, no matter what its initial (high) value. Furthermore, it can be shown from equation (10.87.1) that, in the daytime, it requires 10 seconds for the density to decrease from 10^7 to 10^6; 100 seconds from 10^5 to 10^4, and so on; these are the values given in Table 10.46.

10.88 If the initial electron density at night is greater than 1.6×10^6, the results derived above for daytime are applicable, but for lower densities equation (10.86.1) must be used; the nighttime electron density at any time t is then given by

$$N = N_0 e^{-0.16t} \approx N_0 10^{-0.070t}.$$

This formula shows that, after the electron density falls to 1.6×10^6 at night, the density subsequently decreases by a factor of e every 6 seconds or by a factor of 10 every (roughly) 15 seconds. Thus, the electron density will drop at night from its initial high value to 10^7 in about 1 second, according to the daytime formula, then to 10^6 in roughly 10 seconds, and subsequently by a factor of 10 every 15 seconds, as shown in Table 10.46.

Electron Densities From Delayed Radiation

10.89 At 1 hour after a nuclear explosion, the total delayed beta-particle activity is estimated to be about 400 beta-megacuries per kiloton of fission energy, and since 1 beta-megacurie represents 3.7×10^{16} decays per second (§ 9.163), the rate of beta-particle emission is 1.5×10^{19} per second per kiloton. If the $t^{-1.2}$ rule for the decay of weapon residues is assumed to be applicable (§ 9.171), it follows that for a W-kiloton fission explosion

$$\text{Rate of beta-particle emission} = 1.5 \times 10^{19} W t^{-1.2} \text{ per second,} \tag{10.89.1}$$

where t is the time in hours after the explosion. The average energy per particle may be taken as approximately 1 Mev, i.e., 10^6 ev, and since it requires 34 ev to produce one ion pair, i.e., one electron and one positive ion, in air, it follows that

$$\text{Rate of production of free electrons} = 4.4 \times 10^{23} W t^{-1.2} \text{ per second.} \tag{10.89.2}$$

The energy of the delayed gamma rays from the weapon residues is approximately equal to that of the beta particles and if it is assumed that the $t^{-1.2}$ decay rule is obeyed, the rate of production of free electrons by the gamma rays is also given roughly by equation (10.89.2).

10.90 The actual electron densities established will depend on where the free electrons are produced and on how long they remain free. If a fairly steady source produces S electrons per cubic centimeter per second, the electron density will increase until the rate of removal, e.g., by recombination in the daytime, will just equal the rate of production and then will remain at that value; thus, using equation (10.85.2) for the recombination rate, it follows that, in the daytime,

$$S = \alpha N^2,$$

where N is the steady-state electron density attained.

10.91 It was seen in § 10.38 that when the cloud of radioactive residues is above 45 miles altitude, the bulk of the ionization will be produced within a 10-mile altitude range around a height of 45 miles in two conjugate regions. If the regions are assumed to be circular with a radius R miles, so that the area of each is πR^2 square miles, then the rate of formation of free electrons, due to ionization by beta particles, can be derived from equation (10.89.2) as

$$S = \frac{4.4 \times 10^{23} W t^{-1.2}}{10 \pi R^2 (1.6 \times 10^5)^3} = \alpha N^2$$

where 1.6×10^5 is the factor for converting miles into centimeters. Since, α is 10^{-7}, it follows that

$$N\approx4\times10^6\left(\frac{W}{R^2t^{1.2}}\right)^{1/2} \text{ electrons per cubic centimeter.} \qquad (10.91.1)$$

This relation gives the free electron density, at 45 miles altitude, produced by the delayed beta particles at t hours after a burst of W kilotons fission yield if the debris is spread uniformly over a circular area of radius R miles. The result is applicable to daytime conditions and also at night if the electron density exceeds 1.6×10^6.

10.92 If the electron density is less than 1.6×10^6 at night, the predominant loss rate will be due to attachment of electrons to neutral particles, as given by equation (10.86.1), i.e., $0.16N$. For the same conditions as above, setting S equal to $0.16N$, it follows that the steady-state electron density will be given by

$$N\approx10^7\frac{W}{R^2t^{1.2}} \text{ electrons per cubic centimeter,} \qquad (10.92.1)$$

where t is in hours. The electrons disappear at night by forming negative ions and at sunrise the light will detach the electrons from these ions and the electron density will adjust quickly to the daytime value given by equation (10.91.1).

10.93 If the source of beta particles does not change appreciably in magnitude at the given location, the relationship of electron densities just before and just after sunrise is obtained from equations (10.91.1) and (10.92.1) as

$$N_{\text{day}}\approx1.3\times10^3\sqrt{N_{\text{night}}},$$

provided N_{night} is less than 1.6×10^6 electrons per cubic centimeter at sunrise. It is seen that, in these circumstances, N_{day} will be greater than N_{night}, so that there is an increase in the free electron density at sunrise. This effect was observed at the TEAK and ORANGE high-altitude shots. If the electron density before sunrise is greater than 1.6×10^6, no marked increase will be observed after the sun has risen.

10.94 In order to utilize equations (10.91.1) and (10.92.1) to calculate the steady-state electron densities produced by beta particles in the radioactive cloud, throughout which the weapon debris is supposed to be spread uniformly, it is necessary to know the radius R. The determination of this quantity requires a knowledge of the processes taking place as the cloud rises and spreads horizontally. Since

there is not much known about these processes, models will be used which roughly parallel the behavior observed at high-altitude tests. For a megaton-range burst at an altitude from 15 to 40 miles, it is postulated that the cloud rises to a height of 20 miles above the burst height (§ 10.31), and that its radius increases at a rate of 100 miles per hour. In this case, the radius in miles at any time t hours after the explosion is given by

$$R=100t.$$

With this model the radius at any time can be calculated and the value used, in conjunction with equations (10.91.1) and (10.92.1), to determine the electron density, day or night, as a function of time. The data for the curves in Fig. 10.48a were obtained in this manner, for a 1-megaton fission yield explosion.

10.95 For a megaton burst in the 40- to 70-mile altitude range, it is assumed that the cloud rises to a height of over 100 miles and then drops to 85 miles within a few minutes. The rate of increase of the radius is taken to be 2,000 miles per hour for 30 minutes and 100 miles per hour thereafter. Hence, R in miles is expressed by

$$R=2000t \text{ for } t\leq 0.5 \text{ hour}$$

$$R=950+100t \text{ for } t>0.5 \text{ hour}.$$

These values were used in deriving the results in Fig. 10.48b.

Attenuation of Signals in Decibels

10.96 By combining the data in Fig. 10.29 with equation (10.76.1), it is possible to calculate the extent of attenuation of electromagnetic signals of various frequencies as the result of a 1-megaton fission yield explosion. For an altitude of 45 miles, the collision frequency ν is about 6×10^6 per second. For radio frequencies above 5 megacycles, which are the only ones that will be considered, the value of ω^2 is much greater than ν^2, so that equation (10.76.1) then reduces to

$$A=4\times 10^{-3}\frac{N}{f^2} \text{ decibels per mile,}$$

where f is the wave frequency in megacycles, i.e., $10^{-6}\omega/2\pi$. If the signal beam makes an angle (of incidence) θ with the vertical and traverses a layer 10 miles thick, the total attenuation is

$$A=4\times 10^{-2}\frac{N}{f^2}\sec\theta \text{ decibels.} \tag{10.96.1}$$

The results of equation (10.96.1) are expressed graphically in Fig. 10.96 which shows the signal attenuation in decibels, as a function of frequency, for several values of the angle θ and an electron density of 1 electron per cubic centimeter. The attenuation in any particular situation may be obtained upon multiplying by the actual density N as derived from Fig. 10.29.

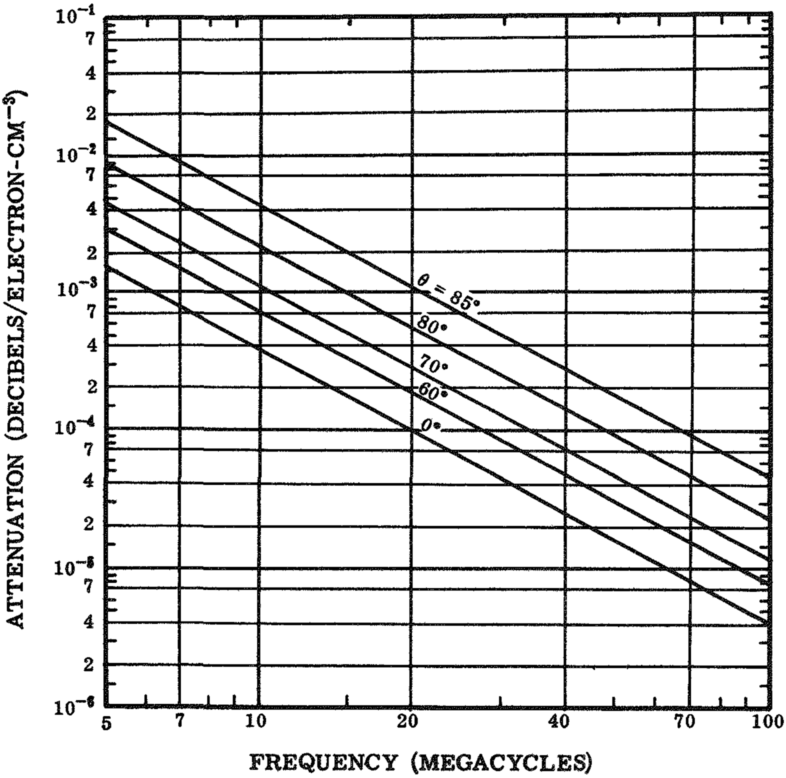


Figure 10.96. Signal attenuation as a function of frequency for various values of the angle of incidence.

10.97 For operational HF circuits the value of sec θ is about 5 under normal conditions, and so it follows from equation (10.96.1) that, for a frequency of 5 megacycles, an electron density of about 5×10^3 electrons per cubic centimeter will produce about 40 decibels of signal attenuation. For a frequency of 20 megacycles, an electron density of almost 10^5 is required to produce the same attenuation. These

densities may be taken as indications of the values required to make an HF circuit inoperative; they were used in this connection in § 10.55 *et seq.*

REFRACTION OF RADIOFREQUENCY SIGNALS

10.98 The index of refraction n of a medium is related to the density of free electrons (N per cubic centimeter); if there are no collisions, then

$$n=\left(1-\frac{Ne^2}{\pi mf^2}\right)^{1/2}, \tag{10.98.1}$$

where e is the charge (in electrostatic units) and m (in grams) is the mass of the electron; f is here the frequency in cycles per second. By inserting numerical values for e and m and expressing f in megacycles, it is found that

$$n=\left(1-\frac{0.8N}{10^4f^2}\right)^{1/2} \tag{10.98.2}$$

or, since electron densities are not known very accurately,

$$n\approx\left(1-\frac{N}{10^4f^2}\right)^{1/2}. \tag{10.98.3}$$

If an appreciable number of neutral particles are present with which the electrons can collide, the collision frequency ν enters the expression for the refractive index in a complex manner. However, if the wave (angular) frequency, ω, is greater than ν, the latter may be ignored.

10.99 At an altitude of 45 miles, where ν is 6×10^6 per second, the expressions given for the refractive index may be used for signal frequencies greater than 10 megacycles. For lower frequencies, the results may be seriously in error. Furthermore, if the electron density exceeds about 10^9, the collision frequency may become much larger than the value given above, and equations (10.98.2) and (10.98.3) will no longer be applicable.

10.100 If an electromagnetic wave crosses a plane interface where the index of refraction changes from 1 to n, the beam will be bent by an amount given by the familiar Snell's law, i.e.,

$$\frac{\sin\theta}{\sin r}=n, \tag{10.100.1}$$

where θ is the angle of incidence and r the angle of refraction. In the passage from the lower atmosphere, where there are essentially no free electrons, into the D-region, where the electron density is N, the bending of the beam can be calculated using equation (10.98.3) to derive the refractive index. This procedure is strictly justifiable only if there is a single, sharp interface where the electron density changes. However, even if the density change is gradual rather than abrupt, the method may be utilized to obtain a rough idea of the amount of bending of the beam.

10.101 Since sin r cannot exceed unity, it follows from equation (10.100.1) that true reflection will take place when sin θ is equal to or greater than n. The values of the angle of incidence, θ, for critical reflection for various values of N and f are given in Fig. 10.71. If N is less than $10^3 f^2$, equations (10.98.2) and (10.100.1) can be approximated by

$$\Delta\theta \approx 3\times 10^{-3}\frac{N \tan\theta}{f^2},$$

where $\Delta\theta$ is the angular change (in degrees) of the ray in passing from electron density zero to density N. If the beam passes on through a 10-mile thick ionized layer into a region of negligible electron density, the signal will once again be traveling in its original direction, but the path will be offset by a horizontal distance given approximately by

$$\text{Offset} \approx \frac{N \sin\theta}{2\times 10^3 f^2 \cos^2\theta}\ \text{miles.}$$

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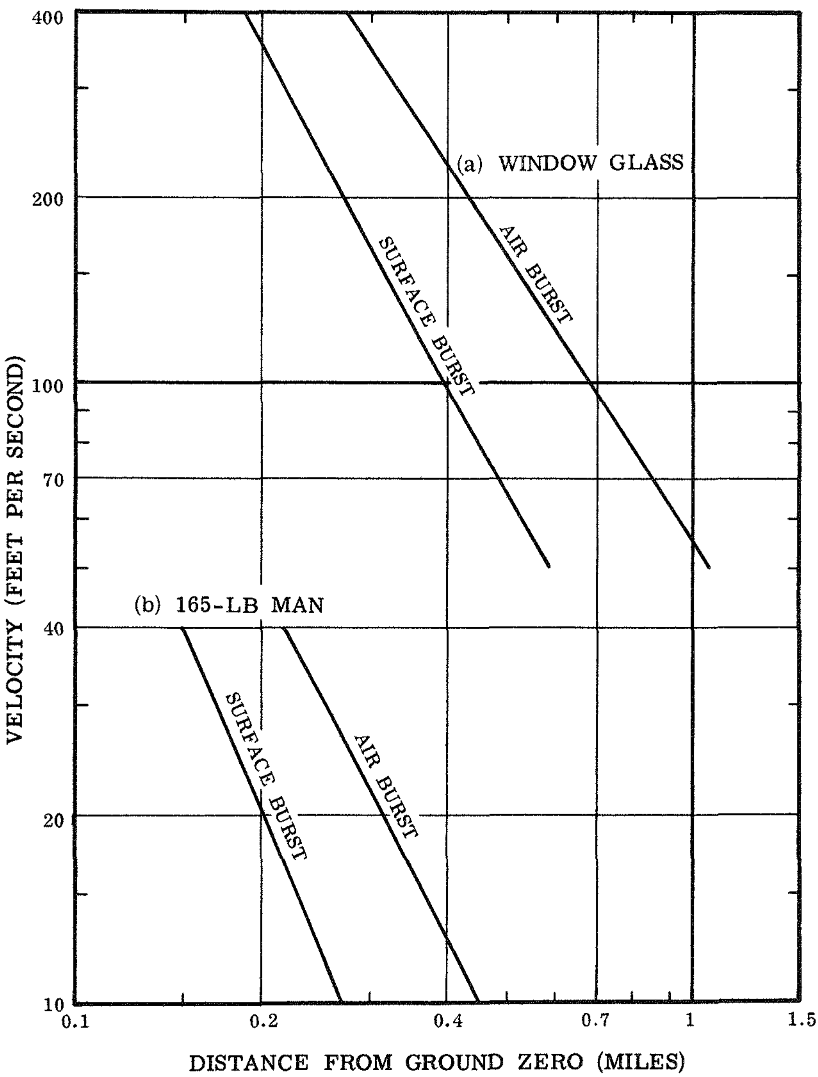

Figure 11.42. Velocities attained after 10 feet displacement by (*a*) 0.1- to 10-gram pieces of window glass, and (*b*) a 165-pound man in 1-kiloton surface and optimized air bursts.

Figure 11.51. The patient's skin is burned in a pattern corresponding to the dark portions of a kimono worn at the time of the explosion.

However, this information has now been supplemented by observations made, especially on anesthetized pigs, both in the laboratory and at nuclear test explosions. The skin of white pigs has been found to respond to thermal radiation in a manner which is in many respects similar to, and can be correlated with, the response of human skin.

11.54 In addition to being chiefly restricted in area to exposed parts of the body, the majority of flash burns show a much smaller depth of penetration of the skin than do flame burns. This is to be expected if the thermal radiation effective in causing burns is emitted during a very short time. In the 20-kiloton explosions over Japan, for example, this was less than 1 second. A very high temperature is thus produced near the surface of the skin in a small interval of time. As a result, some of the characteristics of flash burns, in addition to depth, differ from those of other, more familiar, burns. These differences may be less apparent if the thermal radiation is effective over a longer period of time, e.g., from an air burst in the megaton range.

11.55 Severity of the flash burns in Japan ranged from mild erythema (reddening) to charring of the outermost layers of the skin. Among those who were within about 6,000 feet (1.1 miles) from ground zero, the burn injuries were depigmented lesions (light in color), but at greater distances, from 6,000 to 12,000 feet (1.1 to 2.2 miles) the initial erythema was followed by the development of a walnut coloration of the skin, sometimes called the "mask of Hiroshima."

11.56 Burns of moderate second degree (and milder) usually healed within four weeks, but more severe burns frequently became infected so that the healing process was much more prolonged. Even under the best conditions, it is difficult to prevent burns from becoming infected, and after the nuclear bombings of Japan the situation was aggravated by inadequate care, poor sanitation, and general lack of proper facilities. Nuclear radiation injury may have been a contributory factor in some cases because of the decrease in resistance of the body to infection.

11.57 Experimental flash burns have been obtained both in the laboratory and in nuclear tests which were apparently quite similar to those reported from Hiroshima and Nagasaki. In the more severe cases there was a central charred region with a white outer ring surrounded by an area of erythema. A definite demarcation both in extent and depth of the burns was noted, so that they were unlike contact burns which are generally variable in depth. The surface of the flash burns became dry without much edema or weeping of serum.

11.58 Another phenomenon, which appeared in Japan after the healing of some of the more severe burns, was the formation of keloids, that is, thick overgrowths of scar tissue. It was suggested, at one time, that this might have been due to nuclear radiation, but such a view is no longer accepted. The degree of keloid formation appears

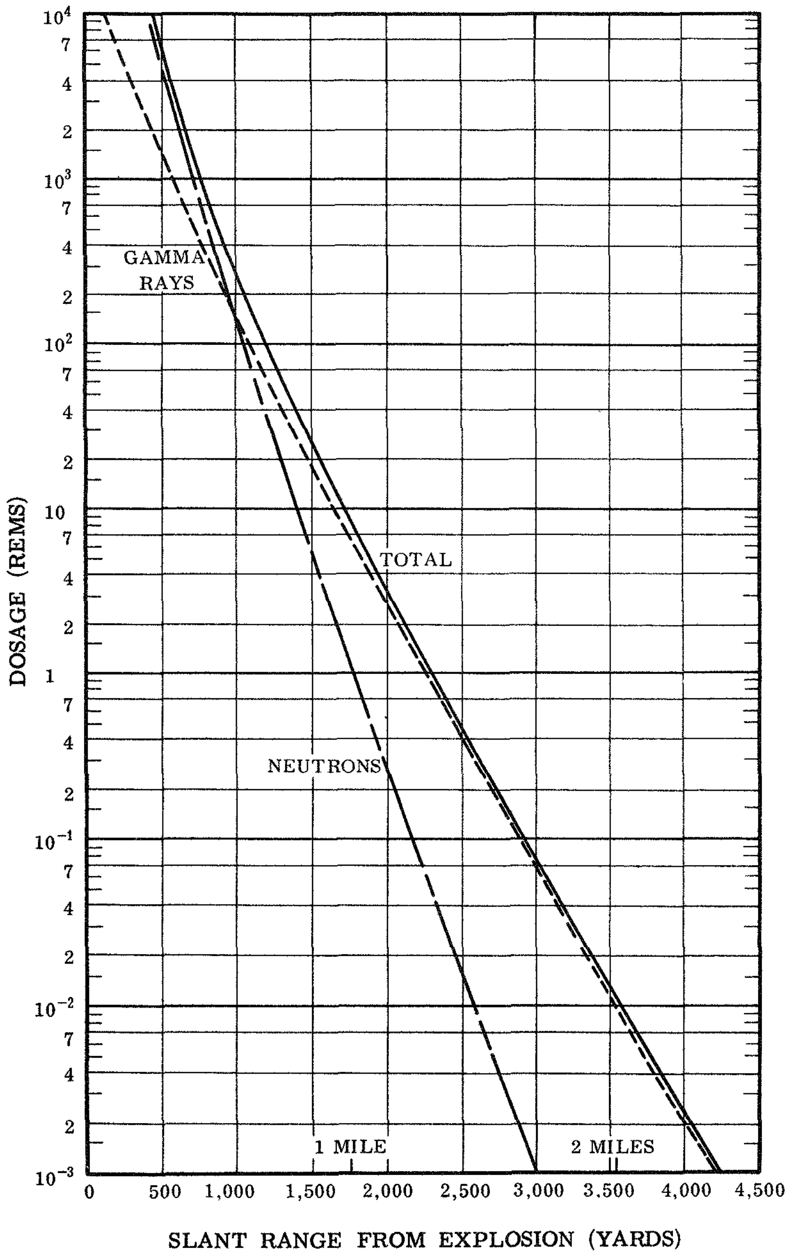

Figure 11.91. Initial gamma-ray and neutron doses as a function of range for a 1-kiloton air burst.

TABLE 11.111

SUMMARY OF CLINICAL EFFECTS OF ACUTE IONIZING RADIATION DOSES

Range	0 to 100 rems Subclinical range	100 to 1,000 rems Therapeutic range			Over 1,000 rems Lethal range	
		100 to 200 rems	200 to 600 rems	600 to 1,000 rems	1,000 to 5,000 rems	Over 5,000 rems
		Clinical surveillance	Therapy effective	Therapy promising	Therapy palliative	
Incidence of vomiting	None	100 rems: 5% 200 rems: 50%	300 rems: 100%	100%	100%	
Delay time	—	3 hours	2 hours	1 hour	30 minutes	
Leading organ	None	Hematopoietic tissue			Gastrointestinal tract	Central nervous system
Characteristic signs	None	Moderate leukopenia	Severe leukopenia; purpura; hemorrhage; infection. Epilation above 300 rems.		Diarrhea; fever; disturbance of electrolyte balance.	Convulsions; tremor; ataxia; lethargy.
Critical period post-exposure.	—	—	4 to 6 weeks		5 to 14 days	1 to 48 hours
Therapy	Reassurance	Reassurance; hematologic surveillance.	Blood transfusion; antibiotics.	Consider bone marrow transplantation.	Maintenance of electrolyte balance.	Sedatives
Prognosis	Excellent	Excellent	Good	Guarded	Hopeless	
Convalescent period Incidence of death	None None	Several weeks None	1 to 12 months 0 to 80% (variable)	Long 80 to 100% (variable)	— 90 to 100%	
Death occurs within	—	—	2 months		2 weeks	2 days
Cause of death	—	—	Hemorrhage; infection		Circulatory collapse	Respiratory failure; brain edema.

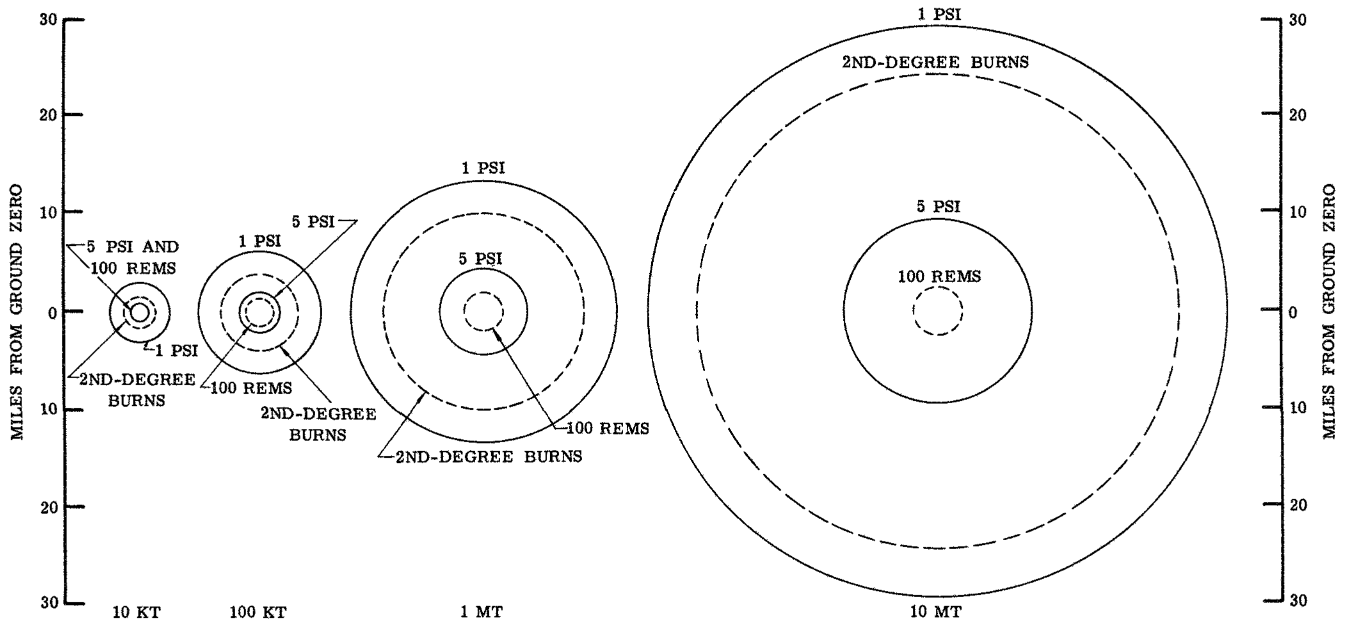

Figure 12.08. Idealized ranges for effects of air burst with the heights of burst optimized to give the maximum range for each individual effect.

casualties. Second-degree burns may be experienced at distances approaching those for 1 psi overpressure and less severe burns may be suffered at much greater distances from ground zero. Eye injury may also occur at even greater ranges and for high-altitude bursts of megaton weapons, this distance may be as much as several hundred miles. Furthermore, in dry, clear weather, many small fires would probably be ignited in newspapers and other thin combustible materials both within and outside of buildings.

Effective Protection Areas

12.11 In Japan, where little evasive action was taken, the survival probability depended upon whether the individual was outdoors or inside a building and, in the latter case, upon the type of structure. At distances between 0.3 and 0.4 mile (530 and 700 yards) from ground zero in Hiroshima the average survival rate, for at least 20 days after the nuclear explosion, was less than 20 percent. Yet in two reinforced-concrete office buildings, at these distances, almost 90 percent of the nearly 800 occupants survived more than 20 days, although some died later from radiation injury. Furthermore, of approximately 3,000 school students who were in the open and unshielded within a mile of ground zero at Hiroshima, about 90 percent were dead or missing after the explosion. But of nearly 5,000 students in the same zone who were shielded in one way or another, only 26 percent were fatalities. These facts bring out clearly the greatly improved chances of survival from a nuclear explosion that could result from the adoption of suitable warning and protective measures.

12.12 As a rough guide, the inner range at which protection in conventional structures could be achieved may be supposed to be that where the overpressure is 5 pounds per square inch and the outer range, beyond which casualties will be small *for an air burst*, is at 1 pound per square inch (or the limit for second-degree burns). As seen above, survival in Hiroshima was possible in buildings at such distances that the overpressure in the open was 15 to 20 pounds per square inch. The somewhat arbitrary choice of an overpressure of 5 pounds per square inch, which was experienced at a little over a mile from ground zero in Japan, is thus very conservative. In any case, it is evident from the circles in Fig. 12.08 that the area over which protection could be effective in saving lives is roughly eight to ten times as great as that in which the chances of survival are small. It may be concluded, therefore, that a considerable proportion of the population "at risk" from a nuclear explosion would be in an area in

which the casualty rate from the immediate effects may be significantly reduced provided protective measures are employed.

12.13 The various circles in Fig. 12.08 refer to an air burst, in which case there is essentially no early fallout. In the event of a burst at or near the surface, the situation would be different. The overpressure ranges would be reduced to roughly three-fourths and the second-degree burn range to about four-fifths of those shown in Fig. 12.08. However, there would be early fallout which might cover very extensive areas, from about 7 square miles for a 1-kiloton explosion to several thousand square miles for a 10-megaton yield (§9.100). Data that can be used for planning purposes are given in Chapter IX, but the conclusions concerning the extent of the hazard from early fallout cannot be expressed in simple diagrammatic form. However, it can be stated quite definitely that, following a surface burst of a high-yield weapon, a very large region extending possibly to three or four hundred miles downwind from the explosion center may become contaminated by the early radioactive fallout. The area affected will be influenced both by the total energy yield of the nuclear weapon and the proportion that is due to fission. The distance at which significant fallout will descend depends on the direction and speed of the wind at all levels from the radioactive cloud down to the ground.

12.14 From the standpoint of the present discussion, it cannot be too strongly emphasized that it is within this possibly large area of early fallout that preplanning of protective measures is of the utmost importance. At locations far from the point of attack, where the immediate effects of the nuclear explosion, i.e., blast, shock, initial nuclear radiation, and thermal radiation, are of absolutely no consequence, the delayed effect of fallout can be extremely serious unless steps are taken, in advance, to achieve protection when the emergency arises.

Relative Importance and Time Scale of Effects

12.15 It is not possible to arrange a single burst which maximizes the potential damage from each of the various immediate and delayed effects of a nuclear explosion. Thus, in a surface burst, the areas affected by blast, thermal radiation, and the initial nuclear radiation are appreciably less than for an air burst of similar energy yield. But, on the other hand, the surface burst is accompanied by early fallout whereas the air burst is not. Even with air bursts, the relative importance of the various effects depends on the height of burst.

12.16 In the following analysis an attempt is made to indicate the relative hazards associated with the various effects, as experienced by

a ground observer, under different burst conditions for a given energy yield. The phenomena are given roughly in the order of their appearance. First, there is the flash of brilliant light accompanied and followed by heat, both of which are part of the thermal radiation. The initial nuclear radiation starts at the same time but may continue after the thermal radiation has ceased. Then ground and water shock, if any, will arrive, followed very soon by the air blast (and sound) wave; then will come the early fallout, if any, which may continue for several hours. The general conclusions are summarized in Table 12.16, the degree (or severity) of a particular effect being indicated by the number of asterisks. The various degrees are relative to each other for a given burst type, and are best interpreted in terms of the descriptions given below.

HIGH-ALTITUDE BURST

Light: Very intense.
Heat: Moderate, decreases with increasing burst altitude.
Initial nuclear radiation: Negligible.
Shock: Negligible.
Air blast: Small on the ground, decreasing with increasing burst altitude.
Early fallout: None.

Summary: The most significant effect will be flash blindness over a very large area; eye burns will occur in persons looking directly at the explosion. Other effects will be relatively unimportant.

AIR BURST

Light: Fairly intense, but much less than for high-altitude burst.
Heat: Intense out to considerable distances.
Initial nuclear radiation: Intense, but generally hazardous out to shorter distance than heat.
Shock: Negligible except for very low air bursts.
Air blast: Considerable out to distances similar to heat effects.
Early fallout: Negligible.

Summary: Blast will cause considerable structural damage; burns to exposed skin are possible over a large area and eye effects over a still larger area; initial nuclear radiation will be a hazard at closer distances; but the early fallout hazard will be negligible.

GROUND SURFACE BURST

Light: Less than for an air burst, but still appreciable.
Heat: Less than for an air burst, but significant.
Initial nuclear radiation: Less than for an air burst.

Shock: Will cause damage within about three crater radii, but little beyond.

Air blast: Greater than for an air burst at close-in distances, but considerably less at farther distances.

Early fallout. May be considerable (for a high-yield weapon) and extend over a large area.

Summary: Except in the region close to ground zero, where destruction would be virtually complete, the effects of blast, thermal radiation, and initial nuclear radiation will be less extensive than for an air burst; however, early fallout may be a very serious hazard over a large area which is unaffected by blast, etc.

SHALLOW UNDERGROUND BURST

Light, heat, and initial nuclear radiation: Less than for a ground surface burst, depending on the extent to which the fireball breaks through the surface.

Shock: Ground shock will cause damage within about three crater radii, but little beyond.

Air blast: Less than for surface burst, depending upon depth of burst.

Early fallout: May be considerable, if the depth of burst is not too large, and in addition there may be a highly radioactive base surge.

Summary: Light, heat, and initial nuclear radiation will be less than for a ground surface burst; early fallout can be significant, and at distances not too far from the explosion the base surge will be an important hazard.

WATER SURFACE BURST

Light: Somewhat more intense than for a ground surface burst.

Heat: Similar to ground surface burst.

Initial nuclear radiation: Similar to ground surface burst.

Shock: Water shock can cause damage to ships and underwater structures to a considerable distance.

Air blast: Similar to ground surface burst.

Early fallout: May be considerable.

Summary: The general effects of a water surface burst are similar to those for a ground surface burst, except that the effect of the shock wave in water will extend farther than ground shock. In addition, water waves can cause damage on a nearby shore by the force of the waves and by inundation.

SHALLOW UNDERWATER BURST

Light, heat, and initial nuclear radiation: Less than for a water surface burst, depending upon how much of the fireball breaks through the surface.

Shock: Water shock will extend farther than for a water surface burst.

Air blast: Less than for a surface burst, depending on the depth of burst.

Early fallout: May be considerable, if the depth of burst is not too large, and in addition there may be a highly radioactive base surge.

Summary: Light, heat, initial nuclear radiation, and blast effects will be less than for a surface burst; early fallout can be significant, but at distances not too far from the explosion the radioactive base surge will be an important hazard. Water waves can also cause damage, as in the case of a water surface burst.

CONFINED SUBSURFACE BURSTS

Light, heat, and initial nuclear radiation: Negligible or none.

Shock: Severe, especially at fairly close distances from the burst point.

Air blast: Negligible or none.

Early fallout: None.

Summary: If the burst does not penetrate the surface, either of the ground or water, the only hazard will be from ground or water shock. No other effects will be significant.

TABLE 12.16

RELATIVE DEGREES OF WEAPON EFFECTS FOR VARIOUS BURST CONDITIONS†

Burst conditions	Thermal radiation		Initial nuclear radiation	Ground or water shock	Air blast	Early fallout
	Light	Heat				
High altitude	****	**	*		*	
Air	***	****	****	*	****	
Ground surface	**	***	***	**	***	****
Water surface	***	***	***	**	***	****
Confined subsurface				****		

†The number of asterisks provides a rough indication of the relative importance of the indicated effect to a ground observer. Four asterisks imply that the effect is the most extensive for the given burst type; a blank space means that the effect is negligible or absent. For a more complete interpretation, see the accompanying text.

12.17 The time sequence referred to in § 12.16 brings up another aspect of nuclear weapons effects that has a bearing on protection. Except very close to ground zero, even the immediate effects do not occur simultaneously. The first, almost instantaneous, indication of a nuclear explosion in the air or on the earth's surface is a brilliant flash of light. In many circumstances, it may be feasible, after observing the flash, to take some appropriate protective action that could greatly minimize the degree of injury suffered. At distances beyond those at which the immediate blast, thermal, and initial nuclear effects of the explosion are significant, there may be some time to make final preparations to decrease the early fallout.

12.18 As a general guide for planning purposes, it is useful to know the magnitudes of the respective immediate effects at a range of distances from an explosion of given yield. This information can be obtained from various figures and tables given in earlier chapters and can be identified from the list in the table of contents at the beginning of the book. A tabular summary of part of the data for air bursts, which may be more convenient for some purposes, is given in Table 12.18. The heights of burst are such as to maximize the various effects. An asterisk indicates that the particular distance is within the fireball; otherwise a blank space implies that the value is too small to be significant. The initial nuclear radiation doses are not given for distances of 5 miles or more for they are extremely small even for a 10-megaton explosion.

BLAST EFFECTS

Effects on Structures

12.19 Injury to individuals both inside and outside a structure may occur because of the blast damage to that structure. Persons in the interior of the building can be injured and trapped by collapse and fire, and those outside can be hurt by flying debris. For these and other reasons, an important aspect of protection is an understanding of the relative ability of different structures to withstand damage from air blast. Both the peak overpressure and the peak dynamic (or wind) pressure determine the amount of the damage, but for certain structures one or the other of these pressures has the dominant effect. For most office-type and residential buildings, including ordinary houses, the extent of destruction is mainly dependent on the peak overpressure, and an approximate correlation between the overpressure and the expected physical damage is given in Table 12.19.

TABLE 12.18

WEAPON EFFECTS FOR AIR BURSTS WITH MAXIMIZED RANGES

Distances from ground zero	Explosion yield				
	1 KT	10 KT	100 KT	1 MT	10 MT
½ mile				(*)	(*)
Overpressure (psi)	4.1	13	46		
Thermal radiation (cal/cm²)	3.8	38	380		
Initial nuclear radiation (rems)	670	6.7×10^3	7.6×10^4		
1 mile				(*)	(*)
Overpressure (psi)	1.5	4.5	14		
Thermal radiation (cal/cm²)	0.9	9.1	91		
Initial nuclear radiation (rems)	9.1	91	1100		
2 miles					(*)
Overpressure (psi)	<1.0	1.7	5.0	16	
Thermal radiation (cal/cm²)	0.2	2.1	21	210	
Initial nuclear radiation (rems)		0.2	1.9	35	
3 miles					
Overpressure (psi)		1.0	2.8	8.6	29
Thermal radiation (cal/cm²)		0.9	9.0	90	900
Initial nuclear radiation (rems)				<1.0	2.6
5 miles					
Overpressure (psi)		<1.0	1.4	4.1	13
Thermal radiation (cal/cm²)		<1.0	3.0	30	300
10 miles					
Overpressure (psi)			<1.0	1.5	4.5
Thermal radiation (cal/cm²)			<1.0	6.6	66
20 miles					
Overpressure (psi)				<1.0	1.7
Thermal radiation (cal/cm²)				1.4	14
50 miles					
Overpressure (psi)					<1.0
Thermal radiation (cal/cm²)				<1.0	1.7

*Inside or close to fireball.

TABLE 12.19

RELATION BETWEEN PEAK OVERPRESSURE AND DAMAGE TO STRUCTURES

Structure type	*Damage*	*Overpressure (psi)*
Wood-frame building, residential type.	Moderate	2 to 3
	Severe	3 to 4
Wall-bearing, masonry building, apartment-house type.	Moderate	3 to 4
	Severe	5 to 6
Multistory, wall-bearing building, monumental type.	Moderate	6 to 7
	Severe	8 to 11
Reinforced-concrete (not earthquake-resistant) building, concrete walls, small window area.	Moderate	8 to 10
	Severe	11 to 15

12.20 This information can be utilized, in conjunction with the overpressure-distance data in Table 12.18, or with the curves in Chapter III, to determine approximately how far from ground zero the respective degrees of damage would be experienced for air bursts of various yields. The height of burst is assumed to be such as to maximize the area of structural damage. For example, it is seen from Table 12.18 that for a 1-megaton air burst a peak overpressure of 3 to 4 pounds per square inch is attained at about 5 miles from ground zero. This is consequently the approximate limit of moderate damage to brick, apartment-house type buildings and of severe damage to wood-frame dwellings.

12.21 The results of a more detailed analysis, based on the nomograph in Fig. 4.58a, are given in Table 12.21. The maximum distances from ground zero for moderate and severe damage to the four types of structures referred to above are recorded for air bursts (at optimum heights) of weapons with yields from 1 kiloton to 10 megatons. For a surface burst, the damage range is three-quarters that for an air burst of the same yield.

TABLE 12.21

MAXIMUM RANGES FROM GROUND ZERO FOR STRUCTURAL DAMAGE FROM AIR BURSTS*

		Explosion yield				
		1 KT	10 KT	100 KT	1 MT	10 MT
Structure type	*Damage*	(Distance in miles)				
Wood-frame building, residential type.	Moderate	0. 66	1. 5	3. 2	6. 6	14
	Severe	0. 47	1. 1	2. 4	5. 5	12
Wall-bearing, masonry building, apartment-house type.	Moderate	0. 53	1. 1	2. 4	4. 7	10
	Severe	0. 34	0. 76	1. 7	3. 5	8. 7
Multistory, wall-bearing building, monumental type.	Moderate	0. 36	0. 76	1. 6	3. 5	7. 4
	Severe	0. 23	0. 55	1. 3	2. 8	6. 1
Reinforced-concrete (not earthquake-resistant) building, concrete walls, small window area.	Moderate	0. 28	0. 61	1. 5	3. 4	7. 2
	Severe	0. 19	0. 44	1. 1	2. 5	5. 9

*For a surface burst the respective distances are three-quarters of those for an air burst of the same yield.

12.22 Information on the effects of 20-kiloton and 1-megaton air bursts on a variety of structures, including many which are damaged by dynamic loading, is given in Tables 12.22 a and b. These refer to "typical" air bursts at heights of 1,850 and 6,800 feet, respectively,

TABLE 12.22a

DAMAGE RANGES FOR 20-KT TYPICAL AIR BURST

Peak Wind Velocity (mph)	Positive Phase Duration (sec)	Peak Dynamic Pressure (psi)	Peak Over-Pressure (psi)	Range from Ground Zero (MILES)	(1000 FT)	
				2		Light damage to window frames and doors, moderate plaster damage out to about 4 miles; glass breakage possible out to 8 miles.
70	0.95	0.09	2.0		10	
				1.8		Fine kindling fuels: ignited.
79	0.94	0.12	2.3		9	Wood-frame buildings: moderate damage. Smoke stacks: slight damage.
				1.6		
93	0.92	0.17	2.7		8	
				1.4		
112	0.90	0.27	3.2		7	Wood-frame buildings: severe damage. Radio and TV transmitting towers: moderate damage. Wall-bearing, brick building (apartment house type): moderate damage.
				1.2		
139	0.86	0.42	4.2		6	
						Wall-bearing, brick buildings (apartment house type): severe damage.
				1.0		Telephone & power lines: limit of significant damage.
190	0.80	0.80	6.0		5	Multistory, wall-bearing buildings (monumental type): moderate damage. Light steel-frame, industrial buildings: moderate damage.
				0.8		
291	0.72	1.50	10.0		4	
						Multistory, wall-bearing buildings (monumental type): severe damage. Light steel-frame industrial buildings: severe damage. Highway and RR truss bridges: moderate damage.
				0.6		
431	0.63	3.90	16.3		3	
						Multistory, steel-frame building (office type): severe damage. Transportation vehicles: moderate damage. Multistory, blast-resistant designed, reinforced-concrete building: moderate damage.
				0.4		
459	0.54	7.50	22.5		2	Multistory, reinforced-concrete, frame building (office type): severe damage. Multistory, blast-resistant designed, reinforced-concrete buildings: severe damage. All other (above ground) structures: severely damaged or destroyed.
260	0.44	2.70	30.0	0.2	1	
				0	0	Ground zero for 20 KT air burst.

Table 12.22b

DAMAGE RANGES FOR 1-MT TYPICAL AIR BURST

Peak Wind Velocity (mph)	Positive Phase Duration (sec)	Peak Dynamic Pressure (psi)	Peak Over-Pressure (psi)	Range from Ground Zero (MILES)	Range from Ground Zero (1000 FT)	
						↑ Light damage to window frames and doors, moderate plaster damage out to about 15 miles; glass breakage possible out to 30 miles.
				10		
44	3.45	0.036	1.2		50	
				9		
51	3.45	0.049	1.4		45	Fine kindling fuels: ignited.
				8		
60	3.44	0.072	1.7		40	
				7		
						Smokestacks: slight damage.
72	3.43	0.11	2.1		35	
				6		Wood-frame buildings: moderate damage.
89	3.40	0.16	2.6		30	
						Radio and TV transmitting towers: moderate damage.
				5		Wood-frame buildings: severe damage. Telephone & power lines: limit of significant damage.
117	3.24	0.28	3.5		25	
						Wall-bearing, brick buildings (apartment house type): moderate damage.
				4		Wall-bearing, brick buildings (apartment house type): severe damage.
177	3.02	0.60	5.5		20	Light steel-frame, industrial buildings: moderate damage.
						Light steel-frame, industrial buildings: severe damage. Multistory, wall-bearing buildings (monumental type): moderate damage.
				3		
278	2.69	1.40	9.4		15	Multistory, wall-bearing buildings (monumental type): severe damage.
						Highway and RR truss bridges: moderate damage. Multistory, steel-frame building (office type): severe damage. Transportation vehicles: moderate damage.
				2		
464	2.25	5.22	18.0		10	Multistory, reinforced-concrete frame buildings (office type): severe damage.
						Multistory, blast-resistant designed, reinforced-concrete buildings: moderate.
307	1.75	3.60	27.0	1	5	
						Multistory, blast-resistant designed, reinforced-concrete buildings: severe. All other (above ground) structures: severely damaged or destroyed.
				0	0	Ground zero for 1 MT air burst.

whereas the results in Table 12.21 and in Figs. 4.58 a and b are for heights of burst which produce a maximum area of damage for each type of structure.

EFFECTS ON PERSONNEL

12.23 For ease of understanding, the effects of air blast on personnel are referred to as either direct or indirect. Among the direct effects are those due to overpressure, such as damage to the ear drums and the lungs (§§ 11.29, 11.31). These occur at close-in distances. An indirect type of injury can arise from displacement of the body as a whole by dynamic (or wind) pressure and its resulting impact with a hard surface (§ 11.33 *et seq.*). This can be experienced at distances where the overpressure (and dynamic pressure) are relatively low, because the maximum wind velocities in the open can still be quite high (Tables 12.22 a and b). Indirect blast injuries can also arise from broken glass and flying debris of various kinds produced by the destruction of buildings. These injuries could be quite numerous over the area in which the overpressure is about 2 pounds per square inch or more.

PROTECTIVE CONSTRUCTION AND EVASIVE ACTION

12.24 It is impractical to construct an aboveground conventional building, e.g., office, apartment, or warehouse, that will resist overpressures greater than 25 psi or more, but by taking certain precautions the blast resistance of any structure can be increased somewhat without adding seriously to its cost. The building should be designed for a prescribed overpressure of a certain duration in order that the structure may have essentially uniform strength in different parts. In this connection, it should be borne in mind that the reflected pressure on a wall facing the blast wave will be more than twice as great as on a side wall (§ 3.71). Sturdy connections between beams and columns, such as are commonly used in earthquake-resistant design, and the extensive use of bracing will generally increase the strength of the structure.

12.25 For large buildings, walls of reinforced concrete, which also contain the frame, will give a structure having maximum blast resistance. Such buildings withstood the blast from a nuclear bomb in Japan (Chapter V), although the interiors were badly damaged by fire. Unreinforced block construction, with brick, concrete, or

glass, is not only much less able to withstand blast than is a reinforced-concrete structure, but produces more flying debris when it is damaged.

12.26 In industrial-type structures, e.g., for housing machine tools, which have walls made of a frangible material, such as asbestos sheet, rather than of metal, the blast wave will destroy the siding with the result that the loading on the frame will be reduced mainly to that from wind drag. The lightweight debris produced will cause little damage to the machines inside the building. However, shelters are necessary to protect personnel in such buildings from flying pieces of frangible material.

12.27 Blast resistant personnel shelters have been tested at nuclear weapon tests at overpressure levels up to 200 pounds per square inch. Animals exposed at overpressures up to 90 pounds per square inch in such shelters have survived. Similar or more modest shelters can be constructed at relatively low cost if they are planned and built concurrently with new construction. Essential features of blast-resistant shelters are structural strength to resist blast loads to the selected overpressure level, an access door of corresponding strength, a protected ventilation system to permit occupancy of the shelter until fires have subsided, and adequate nuclear radiation shielding.

12.28 Where a blast-resistant shelter is not available, protection should be sought in the strongest building that is accessible. Protection against flying debris can be obtained by taking refuge in a location, preferably selected in advance, that is least likely to be entered by blast debris. In addition, individuals should stay away from windows and easily breakable materials, such as plaster walls or ceilings. In the collapse of buildings as a result of blast, heavy members and pieces of structural materials and contents will fall or be hurled about. There is a dual hazard of being hit and trapped; therefore, positions next to walls in basements offer the best protection. Above ground, however, the safest locations are generally near, but not against, walls and away from doors and windows.

12.29 Even if there is no prior warning of a nuclear attack and the first indication is the flash of light, there may still be the opportunity to take some protective action against the effects of blast. In Table 12.29 are given some approximate values of the times which elapse between the instant of the explosion and the arrival of the blast wave front at various distances from ground zero for air bursts of energy yields from 1 kiloton to 10 megatons TNT equivalent. For distances at which the peak overpressure is small, e.g., 1 pound per square inch or less, the times are not included.

TABLE 12.29—ARRIVAL TIME FOR PEAK OVERPRESSURE

Distance (miles)	Explosion yield				
	1 KT	10 KT	100 KT	1 MT	10 MT
	(Time in seconds)				
1	4.3	3.6	3.7	2.5	1.5
2	>9	8.1	7.4	6.5	5.0
3	--------	>13	12	11	9.5
5	--------	--------	21	20	16
7	--------	--------	>30	28	26
10	--------	--------	--------	42	37
20	--------	--------	--------	>90	83
30	--------	--------	--------	--------	>130

12.30 It is seen that at 10 miles from a 10-megaton air burst, which is within the area where protection against blast could be effective, some 37 seconds would elapse before arrival of the blast wave. If prompt action is taken, a person in a building could reach a position of the type indicated above. In the open, some protection against the blast may be obtained by falling prone, and remaining in that position until the wave has passed. In the prone position, with the head directly toward or directly away from the explosion, the area of the body exposed to the onrushing blast wave is relatively small and the danger of displacement is thereby decreased (cf. § 11.38).

THERMAL RADIATION EFFECTS

EFFECTS ON PERSONNEL

12.31 The main direct effects of thermal radiation on human beings are skin burns, generally called flash burns to distinguish them from flame burns, and permanent or temporary eye damage. Burns are classified by "degree"; first-degree burns being mild in nature, roughly similar to moderate sunburn; they should heal without special treatment. Second-degree burns are associated with blister formation and if a significant area of the body is involved, medical attention is necessary (§ 11.44 *et seq.*). The approximate limiting distances from air bursts of various total yields at which first- and second-degree burns of exposed (light-colored) skin may be expected are given in Table 12.31. Third-degree burns, which involve the entire thickness of the skin, can occur at shorter ranges. For a surface burst, the respective distances are decreased to about four-fifths of the values in the table. The ranges shown are actually from the burst point

rather than from ground zero, but at the heights of burst that maximize the distances over which burns are experienced, the differences are small.

TABLE 12.31

RANGES FROM GROUND ZERO FOR BURNS TO BARE SKIN FROM AIR BURSTS*

	Explosion yield				
	1 KT	*10 KT*	*100 KT*	*1 MT*	*10 MT*
	(Distance in miles)				
First-degree burn	0. 7	1. 9	5. 3	14	>30
Second-degree burn	0. 5	1. 5	4. 0	11	24

*For a surface burst the distances are about four-fifths those for an air burst of the same yield.

12.32 The data presented in Table 12.31 are applicable to reasonably clear atmospheric conditions. Fog or mist near the ground or a layer of cloud between the point of the explosion and the ground would attenuate the thermal radiation and thus decrease the ranges at which flash burns may be experienced by exposed persons. However, snow on the ground or cloud layers above the explosion provide reflecting surfaces which increase these ranges.

12.33 Eye injuries are of two main types: temporary (flash blindness) and permanent (chorioretinal burns), as described in § 11.69 *et seq.* Both kinds of injury can occur at great distances from the explosion, considerably greater even than those for first-degree burns given in Table 12.31. The nature and extent of the eye injury depends on the yield and type of burst, on the orientation of the observer to the burst, on the clarity of the atmosphere, and on the size of the pupil opening. As a general rule, permanent eye injury would be expected only in those persons who were looking directly at the fireball. Flash blindness, on the other hand, could be quite general over a large area.

PROTECTIVE MEASURES

12.34 In an air or surface burst, the thermal radiation is received in two pulses, in each of which there is a maximum of intensity followed by a decrease. If an individual is caught in the open or is near a window in a building at the time of a nuclear explosion, evasive action to minimize flash burn injury should be taken, if possible, before the maximum in the second pulse. At this time only 20 percent of the thermal energy will have been received, so that a large proportion can be avoided if shelter is obtained before or soon after

the second thermal maximum. The elapsed times between the instant of the explosion and the second thermal maximum for air and surface bursts of various energy yields are recorded in Table 12.34. From this table it is seen that the prospects of being able to take evasive action are not good for air or surface bursts of low energy yield, but some possibility may exist for explosions in the megaton range.

TABLE 12.34

TIME TO SECOND THERMAL MAXIMUM

	Explosion yield				
	1 KT	*10 KT*	*100 KT*	*1 MT*	*10 MT*
Time (seconds)	0.03	0.1	0.3	1.0	3.2

12.35. The major part of the thermal radiation travels in straight lines, and so any opaque object interposed between the fireball and the exposed skin will give some protection. This is true even if the object is subsequently destroyed by the blast, since the main thermal radiation pulse is over before the arrival of the blast wave.

12.36 At the first indication of a nuclear explosion, by a sudden increase in the general illumination, a person inside a building should immediately fall prone, as described in § 12.30, and, if possible, crawl behind or beneath a table or desk or to a planned vantage point. Even if this action is not taken soon enough to reduce the thermal radiation exposure greatly, it will minimize the displacement effect of the blast wave and provide a partial shield against splintered glass and other flying debris. An individual caught in the open should fall prone to the ground in the same way, while making an effort to shade exposed parts of the body. Getting behind a tree, building, fence, ditch, bank, or any structure which prevents a direct line of sight between the person and the fireball, if possible, will give a major degree of protection. If no substantial object is at hand, the clothed parts of the body should be used to shield parts which are exposed. There will still be some hazard from scattered thermal radiation, especially from high-yield weapons at long range, but the decrease in the direct radiation will be substantial.

12.37 Clothing of the proper kind provides good protection against flash burns. Materials of light color are usually preferable to dark materials because the former reflect the radiation. Clothing of dark shades absorbs the thermal radiation and may become hot enough to ignite, so that severe flame burns, which are more serious that the flash burns, may result. Woolen materials give better protection than those of cotton of the same color, and the heavier the fabric the

greater the protection. An air space between two layers of clothing is very effective in reducing the danger of flash burns.

12.38 Protection against eye injury is difficult, especially for those persons who happen to be facing the burst point. The blink reflex, i.e., the automatic blinking of the eye, which requires 0.15 second, may be helpful in providing some protection from air and surface bursts in the megaton range. It is doubtful, however, if much can be done at those distances where the same total amount of thermal energy is received from weapons of lower energy. In a nuclear explosion at high altitude, that is, at heights above 20 miles, the thermal radiation is emitted in a single rapid pulse. Assuming the total thermal energy received by a person at a particular location is sufficient to cause flash burns or eye injury, it seems improbable that any evasive action will be effective, as even the involuntary blink will not be in time to help very much. Ordinary sunglasses will provide little or no protection against eye damage, since much more opaque material would be required to decrease the radiation intensity. In all cases individuals should make every effort to avoid looking toward the fireball.

Fire Protection

12.39 After a nuclear attack on an urban area, extensive fires may develop as they did in Japan. Such fires were started both directly by thermal radiation and by secondary blast effects, i.e., overturning of stoves, short circuiting of electrical wires, etc. (§ 7.69). Appropriate fire control action may be directed along three lines, namely, (1) reduction of potential ignition points, (2) provision for isolation or rapid extinction of ignitions to prevent formation of large fires, and (3) minimization of the consequences should large-scale fires develop.

12.40 Since the elimination of wood as a construction material for houses is virtually impossible, potential ignition points can be decreased by continuous upkeep of existing wood structures and by taking steps to keep yards free from all combustible trash. As stated in § 7.57 *et seq.*, it was clearly demonstrated at the 1953 tests in Nevada that a well-maintained house, with a yard free from trash, is much more capable of withstanding the thermal effects of a nuclear explosion than is a poorly-maintained house or one with an unkept yard. Fire-resistive furnishings, e.g., draperies, rugs, etc., made of vinyl plastic or wool, also proved to be advantageous in these tests.

12.41 The second aspect of fire control action is to plan and train for the elimination of small fires before they can grow into serious ones.

In Japan the fires were so numerous and spread so rapidly that it would have been beyond the capability of regular fire departments to deal with them even if the latter had survived the bombings. The training of private individuals in emergency methods of firefighting, such as were developed in Europe during World War II, is therefore desirable. By extinguishing small fires soon enough, the number of serious fires may be sufficiently small to be dealt with by professional firefighters.

12.42 Conventional methods for preventing the spread of large fires, by the use of natural and artificial fire breaks, were not too successful in Japan, for the reasons mentioned in § 7.72. Nevertheless, consideration should be given to the provision of adequate fire breaks and to the zoning and planning of urban areas. As seen in § 7.55, the potential for the development and spread of fires is greatest in wholesale distribution and slum residential areas. Dispersal and protection of utilities and emergency services should be included in such planning.

INITIAL NUCLEAR RADIATION

Effects on Personnel

12.43 The initial nuclear radiation consists of gamma rays and neutrons received during the first minute after the explosion. Doses of this radiation up to 100 rems, over the whole body, would have little or no immediate observable effects on exposed individuals. The only effect expected might be a slight feeling of fatigue in some people. Many persons receiving larger doses, up to 200 rems, would not be greatly affected by the radiation, except for blood changes. For the present purpose, however, it will be supposed that a whole-body dose of 100 rems will cause few, if any, casualties requiring medical attention. At the other extreme, it is probable that every person receiving 1,000 rems over the whole body will become sick within 4 hours (or less) of exposure and will die in 2 or 3 weeks. Between these extremes there is a great deal of variation in the expected effects on personnel, but at an exposure of around 400 to 500 rems, all will be nauseated and vomit on the first day, and most will require medical care. However at this exposure, at least one-half of the people will probably recover.

12.44 The actual distances from air bursts of various yields at which the initial nuclear radiation will produce doses of 100, 500, and 1,000 rems, respectively, to completely unprotected individuals are

shown in Table 12.44. However, the heights of burst which maximize these distances are such that the latter are not very different from the ground zero ranges. For purposes of comparison, the distances for an overpressure of 5 pounds per square inch and for second-degree flash burns of exposed skin are included. It is seen that the hazards from blast and thermal radiation extend to much greater distances than do those from initial nuclear radiation, especially for weapons of yields in excess of 10 kilotons. For example, an individual 2 miles from a 1-megaton burst probably would show no significant symptoms of nuclear radiation sickness, but the thermal radiation exposure would be 210 calories per square centimeter (see Table 12.18). Less than 7 calories per square centimeter are sufficient to produce a second-degree skin burn from an explosion of 1 megaton. The corresponding blast wave overpressure of 18 pounds per square inch would cause severe damage to the strongest conventional structures (cf. Table 12.19).

TABLE 12.44

RANGES FROM GROUND ZERO FOR VARIOUS INITIAL NUCLEAR RADIATION DOSES FROM AIR BURSTS*

	Explosion yield				
	1 KT	*10 KT*	*100 KT*	*1 MT*	*10 MT*
	(Distances in miles)				
Radiation Dose					
100 rems	0.7	1.0	1.3	1.8	2.4
500 rems	0.6	0.8	1.1	1.5	2.1
1,000 rems	0.5	0.7	1.0	1.4	2.0
Other Effects					
5 psi	0.4	0.9	2.0	4.3	9.2
Second-degree burns	0.5	1.5	4.0	11	22

*The distances for a specified radiation dose are slightly less for a surface burst.

PROTECTION FROM INITIAL NUCLEAR RADIATION

12.45 It is apparent that for weapons with yields greater than 10 kilotons, the regions in which large doses of initial nuclear radiation could be received are those of high blast pressure and intense thermal radiation. Protection against all three effects would be provided by a massive reinforced, fire-resistant building. An 18-inch thickness of concrete, for example, would reduce the fatal dose of 1,000 rems to the tolerable one of about 100 rems. Thus, aboveground buildings of massive construction would provide some protection against the initial nuclear radiation. Additional protection may be obtained in basements beneath substantial concrete floor slabs. The surrounding

earth also helps in this connection; a 26-inch thickness of earth attenuates the radiation by a factor of about ten and 3 feet by about thirty.

12.46 The immediate evasive action suggested earlier for limiting the effects of thermal radiation and blast to a person in the open may assist, to a lesser extent, in reducing the dose of initial nuclear radiation. From high-yield weapons, in particular, a second or two elapses before much of the nuclear radiation is delivered at distances where survival is possible (§ 8.43). Table 12.46 gives the percentage of the total initial gamma-radiation dose received at given distances from 20-kiloton and 5-megaton explosions as a function of time. The total unshielded dose would be about 4,500 roentgens in each case.

TABLE 12.46

INITIAL GAMMA-RADIATION DOSE AS A FUNCTION OF TIME

Explosion yield	*Distance (miles)*	*Time (seconds)* 1	2	4	7	10	15	20
		Percentage of initial gamma-radiation dose delivered						
20 KT	0.5	67	78	88	95	97	100	-----
5 MT	1.5	5	17	43	76	90	98	100

12.47 As shown by the table, there is some possibility of reducing the radiation dose by immediate evasive action. However, from the numbers given above for the attenuation by concrete and earth, it is obvious that a nuclear radiation shield must be very massive if it is to be effective. Normal clothing, for example, will do little to attenuate initial nuclear radiation, although it may provide complete protection from thermal radiation. Another difficulty in connection with obtaining shelter in the open is the scattering of nuclear radiation, so that it may reach a person from many directions and not just along a direct line from the point of explosion.

RESIDUAL NUCLEAR RADIATION

FALLOUT HAZARD

12.48 The principal effects on personnel from residual radiation are similar to those from comparable doses of initial nuclear radiation as described in the preceding section. However, the hazards of exposure to residual radiation are entirely different from exposure to initial radiation and these hazards are described in this section.

12.49 Protection against residual nuclear radiation occupies a position of special significance. Because the early fallout can cover

an area much larger than that over which blast, thermal radiation, and initial nuclear radiation are significant, it is possible for people to become casualties at such distances from the explosion that the immediate effects are negligible or completely absent. As noted earlier, it is not feasible to state the degree of hazard from residual radiation in a reasonably accurate manner because it is so highly dependent upon conditions, especially wind speeds and directions over a considerable height. It is certain, however, that a surface burst in the megaton range will lead to contamination of very large areas by early fallout. This fallout will reach the ground very soon after the explosion at near distances, but at distances of several hundred miles, up to 24 hours may elapse before the fallout starts to arrive.

12.50 The early fallout hazard is of two main kinds: one results from the actual contact of the radioactive material with the skin, causing what are called "beta burns" produced by the action of the beta particles, and the second is due to the continuous exposure of the body to gamma rays, both direct and scattered, from fallout particles. It is with the second of these hazards that the discussion here will be mainly concerned. The protective measures for use against beta burns are chiefly associated with keeping the dust-like particles off the skin. If the fallout dust does get on the skin, it should be immediately washed off with soap and water. The possible hazard from entry of radioactive material into the body by ingestion will be considered later (§ 12.66 *et seq.*).

INDUCED RADIOACTIVITY

12.51 In addition to the radioactive fallout, there may be a residual radiation hazard near ground zero caused by induced activity resulting from the capture of neutrons by various elements in the soil, especially sodium and manganese. The induced-activity hazard may exist on the ground after an air burst when the initial fallout is virtually absent. However, this activity not only decays much more rapidly than does that from fallout, but it extends only a short distance (1 mile or less) from ground zero. Since the destruction in this area would be considerable, the only persons entering it for some time after the explosion should be rescue teams and others performing urgent missions. Such teams would be equipped with instruments to inform them of the radiation hazard.

PROTECTIVE MEASURES

12.52 Assuming the population is to remain in the fallout area, and not be evacuated, it is necessary to obtain protection which

attenuates the gamma radiation. The basic principle to be borne in mind is that any massive or thick material will decrease the nuclear radiation level to some extent, whereas lighter construction, e.g., window areas, hollow, thin, or light walls, etc., permits the radiation to penetrate. A layer of concrete 8 inches thick or of earth 12 inches thick will yield an attenuation factor of 10; [2] doubling these thicknesses will increase the factor to 100. Thus, each extra foot of earth between an individual and the fallout will increase the protection factor tenfold. It should be remembered that scattered radiation will come from many directions, and so protection is necessary from all directions, either by the use of a mass of material or by distance.

12.53 Information has been published that describes procedures and standards for evaluating the potential of existing structures as fallout shelters and for modifying such structures to improve their effectiveness in this respect. The recommended procedures and standards may also be utilized in the design of new structures. Furthermore, instructions for building simple and effective fallout shelters are readily available. Basically, a fallout shelter is a structure with massive walls and ceiling. Practical materials of construction are earth, concrete, or solid masonry. Attenuation of the gamma radiation is provided by absorption in these materials and by the distance separating the fallout particles from the people in the shelter.

12.54 Since a shelter may have to be occupied continuously for periods as long as 2 weeks, until the natural decay of the radioactivity outside will allow the people to emerge, stocks of food and other supplies will be required. Where fallout arrives soon after the explosion, the early radiation dose rate will be high. It may then be necessary to wait several days before it is possible to come out of the shelter for more than a limited period without risking a radiation dose of sufficient magnitude to cause serious illness. In the path of the fallout, the early radiation levels will be lower at more distant points from the explosion, and the time necessary to occupy the shelter will be shorter, unless "hot spots" are present (§ 9.55). However, in any area where contamination is at all significant, it will probably be necessary to spend the first day or two after the burst sheltered from the residual gamma radiation. It is during the period immediately following the nuclear explosion, when the radiation level is at its highest, that protection is most important.

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[2] It should be noted that more than twice these thicknesses of concrete (18 inches) and of earth (26 inches) are required to attenuate the initial nuclear radiation to the same extent (§ 12.45) because the energy of the initial gamma rays is greater than in the residual (fallout) radiation.

12.55 A fallout shelter of the kind referred to in §12.53 will provide a protection factor of about 200 from the residual radioactivity; in other words, the dose rate in the shelter will be only ½ percent of that measured outside at a height of 3 feet above the ground. Where a shelter is not available, a similar protection factor from radiation can be obtained in the following manner in a small area of the basement of a two-story house. A sturdy table is placed in a corner adjacent to an unexposed outer wall and covered with 10 to 12 inches of soil, sandbags, solid concrete block, etc., according to what is available. If there are no heavy partitions or walls near the corner of the basement chosen, a layer of sandbags or concrete blocks should be stacked along the walls up to the height of the material on top of the table. Within the area under the table, there will be a protective factor of at least 100 from fallout radiation. The disadvantage of this type of protection is that it is unlikely that stocks of food and water would be available within the shelter, so that it could not be occupied continuously for an extended period, as could the more permanent type outlined previously. In almost any house with a buried basement, having uniformly thick exterior walls, a protection factor of 20 to 40 is possible. The maximum protection can be obtained near the floor and in the corners of the basement adjacent to an unexposed outer wall.

12.56 Before leaving a shelter, either temporarily or permanently, it is highly desirable that the radiation dose rate, both in the immediate area of the shelter and in the surrounding vicinity, be known. Marked variations in fallout patterns have been observed in weapons tests, with unexpected areas (hot spots) of exceptionally high activity. Hence, it is not sufficient to know merely that a nearby location is relatively safe. Communications equipment, e.g., battery-powered radios, and radiation measuring instruments should be in shelters. Otherwise it will not be possible to obtain information on radiation dose rates in the locality and in the immediate vicinity of the shelter, particularly at early times when high radiation levels will prevent radiation monitors from moving safely and freely about the community. As a rough rule-of-thumb, it may be stated that for every sevenfold increase in time, the radiation level will decrease by a factor of 10, provided the fallout is complete. For example, the radiation level at the end of 7 days will have fallen to roughly one-tenth of that at the end of 1 day. At the end of 49 days, it will have decreased by a factor of 100, etc.[3]

12.57 It is appropriate to mention here that whether or not fallout is visible to the eye, its measurement requires the use of suitable

[3] The rule is applicable to any unit of time; thus at 7 hours the residual radiation level will be one-tenth of that at 1 hour, at 14 hours it will be one-tenth of that at 2 hours, and so on, provided the fallout is complete at both times.

instruments sensitive to nuclear radiations. Some, although perhaps not all, of the fallout in the Marshall Islands, after the test explosion of March 1, 1954 (§ 9.100 *et seq.*), could be seen as a white powder or dust. This was due, partly at least, to the light color of the calcium oxide or carbonate of which the particles were mainly composed. It is probable that whenever there is sufficient fallout to constitute a hazard, the dust will be visible. Nevertheless, continuous monitoring with instruments for radioactive contamination would appear to be essential in all areas in the vicinity of the burst.

Radiological Surveys

12.58 As soon after a nuclear explosion as conditions permit, radiological monitoring surveys will have to be initiated for the purpose of developing information on the extent and levels of the contamination. At early times in heavily contaminated areas, where dose rates will be very high, only the most limited amount of monitoring can be accomplished by individuals with hand-carried instruments. In these circumstances, some kind of remote radiation monitoring equipment may be necessary. This will permit the monitor to remain within the shelter while taking readings of the dose rate outside.

12.59 The most rapid method for obtaining radiation levels in a large area is by aerial survey. Because of their long range in air, gamma rays can be detected by sensitive instruments at a height of a few thousand feet. Low-flying airplanes or helicopters, carrying suitable radiation instruments for measuring dose rates, can survey large areas unimpeded by damage on the surface and by impassable streets and roads. Moreover, by making initial flights at an altitude of 1,600 feet or so, the dose rates are only about 1 percent of those on the ground, so that the hazard to the monitor is decreased accordingly.

12.60 The dose rates measured at an altitude must be multipled by an appropriate factor to give the approximate dose rates near the ground. This factor will depend primarily on the height above the ground and nature of the terrain. In the absence of more specific information, the data in Fig. 9.181 may be used to estimate the attenuation factor at a known altitude with reference to that at a height 3 feet above the ground.

12.61 The aerial survey is important because it can be made readily and can provide information which might be impossible to obtain in any other way at the time of interest. Nevertheless, such a survey can serve only as a rough guide and should be made only after all the early fallout is out of the air and on the ground. For points of special

interest, the aerial survey must be supplemented by measurements made on the ground when it is safe to do so. The information obtained from the aerial survey will help, however, in planning the ground survey. In this way, the first appreciation of the broad aspects of the radiological situation will lead to the determination of conditions at critical points, to the establishment of dose-rate contours, and to the location of contaminated hot spots as well as the safest areas.

RADIATION DOSES AND TIMES IN CONTAMINATED AREAS

12.62 For the planning of defensive actions in connection with the residual activity from fallout or for carrying out survey operations in an area contaminated by the residues from a nuclear explosion, it is necessary either to make some estimate of the permissible time of stay for a prescribed gamma-radiation dose (in roentgens or rems) or to determine the dose which would be received in a certain period of time. The basic data are presented in the form of graphs in Chapter IX, but the same results may be expressed, in a somewhat more limited form, in tables that are more convenient for some purposes.

12.63 If the radiation dose rate (in roentgens or rems per hour) is known at a certain time at a given location, Table 12.63 may be used to determine the dose rate at any other time at the same location, *assuming that the fallout has descended completely and there has been no change other than that resulting from natural radioactive decay.* The same table can be utilized to determine the time after the explosion at which the dose rate will have attained a specific value. Suppose, for example, that at 5 hours after the explosion the measured dose rate is 6 roentgens per hour; when will it have decreased to 1 roentgen per hour? To obtain the answer, find the line in the left-hand column indicating "5 hours," and follow this horizontally until the value nearest to 6 is reached; this is 5.8, which is lower than the actual dose rate. Now proceed vertically down this column until the indicated value is somewhat less than 1.0; it is seen to be roughly 25 hours.

12.64 To determine the allowable time of stay in a contaminated area before a specified total dose is received, Table 12.64 may be employed if the dose rate at the time of entry is known. Suppose that upon entering a contaminated area at 8 hours after the explosion, the dose rate (R) is found to be 45 roentgens per hour. A competent authority has decided that exposed persons in the area may receive a total dose (D) of 25 roentgens, without endangering themselves, in order to perform an important mission; how long can they stay?

TABLE 12.63

FALLOUT ACTIVITIES AT VARIOUS TIMES AFTER A NUCLEAR EXPLOSION

Time after explosion	Dose rate																			
6 min	16	32	66	95	127	159	318	477	636	795	954	1,272	1,590							
12 min	7	14	28	41	55	69	138	207	276	345	414	552	691	1,380						
18 min	4.3	8.6	17	25	34	43	86	129	172	216	259	344	431	862	1,290					
30 min	2.3	4.5	9.1	13	18	23	45	68	91	114	136	182	227	456	681	908	1,140			
42 min	1.5	3.0	6.0	9.1	12	15	30	46	61	76	91	122	152	304	456	608	760	912	1,220	
1 hr	1.0	2.0	4.0	6.0	8.0	10	20	30	40	50	60	80	100	200	300	400	500	600	800	1,000
1 hr 30 min	0.6	1.2	2.4	3.7	4.9	6.1	12	18	24	31	37	48	61	122	183	244	305	366	488	610
2 hr	0.4	0.9	1.8	2.6	3.5	4.4	8.7	13	18	22	26	35	44	87	131	175	219	262	350	437
3 hr	0.3	0.5	1.1	1.6	2.1	2.7	5.4	8.0	11	13	16	21	27	54	80	107	134	161	214	268
5 hr		0.3	0.6	0.9	1.2	1.5	2.9	4.4	5.8	7.3	8.7	12	15	29	44	58	73	87	116	145
7 hr			0.4	0.6	0.8	1.0	1.9	2.9	3.9	4.9	5.8	8	10	19	29	39	49	58	78	97
10 hr				0.4	0.5	0.6	1.3	1.9	2.5	3.2	3.8	5.1	6.4	13	19	25	32	38	51	64
15 hr					0.3	0.4	0.8	1.2	1.6	1.9	2.3	3.2	3.9	7.8	12	16	19	23	31	39
1 day							0.5	0.7	0.9	1.2	1.3	1.8	2.3	4.5	6.8	9.0	12	13	18	23
1 d 12 hr							0.3	0.4	0.6	0.7	0.9	1.2	1.5	2.9	4.4	5.8	7.3	8.7	12	15
2 d							-		0.4	0.5	0.6	0.8	1.0	1.9	2.9	3.9	4.9	5.8	7.8	10
4 d												0.3	0.4	0.8	1.3	1.7	2.1	2.5	3.3	4.2
1 wk														0.5	0.7	0.9	1.2	1.4	1.8	2.3
2 wk																0.3	0.4	0.5	0.6	0.8
4 wk												---							0.3	0.4

TABLE 12.64

ALLOWABLE STAY TIME IN AREA CONTAMINATED BY FALLOUT FROM A NUCLEAR EXPLOSION

	Time of entry in hours after the explosion																		
	0.1	0.2	0.5	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40
D/*R*	Duration of exposure (in hours and minutes) required to produce specified values of *D*/*R* for various times of entry after the explosion.																		
0.2	1-11	0-25	0-15	0-14	0-13	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12
0.3	9-40	1-00	0-22	0-22	0-20	0-19	0-19	0-19	0-19	0-18	0-18	0-18	0-18	0-18	0-18	0-18	0-18	0-18	0-18
0.4	312-24	2-22	0-42	0-31	0-27	0-26	0-26	0-25	0-25	0-25	0-25	0-25	0-25	0-24	0-24	0-24	0-24	0-24	0-24
0.5	∞	6-12	1-02	0-42	0-35	0-34	0-32	0-32	0-32	0-31	0-31	0-31	0-31	0-31	0-31	0-30	0-30	0-30	0-30
0.6	------	19-20	1-26	0-54	0-44	0-41	0-39	0-39	0-38	0-38	0-38	0-37	0-37	0-37	0-37	0-37	0-37	0-36	0-36
0.7	------	82-06	2-05	1-08	0-52	0-49	0-47	0-46	0-45	0-45	0-44	0-44	0-44	0-44	0-43	0-43	0-43	0-43	0-42
0.8	------	624-48	2-56	1-23	1-02	0-57	0-54	0-53	0-52	0-51	0-51	0-51	0-50	0-50	0-49	0-49	0-49	0-49	0-49
0.9	------	2,000-00	4-09	1-42	1-12	1-05	1-02	1-00	0-59	0-58	0-58	0-57	0-57	0-57	0-56	0-55	0-55	0-55	0-55
1.0	------	∞	5-56	2-03	1-23	1-14	1-10	1-08	1-06	1-05	1-05	0-04	1-04	1-03	1-02	1-02	1-02	1-01	1-01
1.25	------	--------	15-30	3-13	1-54	1-38	1-31	1-28	1-25	1-24	1-23	1-22	1-21	1-20	1-19	1-18	1-17	1-17	1-16
1.5	------	--------	48-20	4-57	2-30	2-05	1-54	1-49	1-45	1-43	1-41	1-40	1-39	1-37	1-36	1-34	1-33	1-33	1-32
2.0	------	--------	1,562-00	11-52	4-06	3-13	2-46	2-35	2-29	2-24	2-20	2-18	2-16	2-13	2-10	2-08	2-06	2-05	2-04
2.5	------	--------	∞	31-00	6-26	4-28	3-48	3-28	3-16	3-08	3-03	2-59	2-55	2-51	2-46	2-45	2-40	2-38	2-36
3.0	------	--------	--------	96-39	9-54	6-09	5-01	4-28	4-10	3-58	3-49	3-43	3-38	3-30	3-24	3-17	3-14	3-11	3-08
4.0	------	--------	--------	3,124-00	23-43	11-05	8-12	6-57	6-16	5-50	5-33	5-19	5-10	4-58	4-44	4-32	4-26	4-20	4-15
6.0	------	--------	--------	∞	193-19	35-35	19-48	14-43	12-19	10-55	10-02	9-24	8-57	8-19	7-46	7-15	7-01	6-48	6-34
10.0	------	--------	--------	--------	∞	728-49	124-00	59-18	39-34	30-39	25-42	22-35	21-32	17-52	15-41	13-57	13-05	12-24	11-42

D/*R*=Allowable dose in roentgens divided by dose rate in roentgens per hour at time of entry.

The allowable dose (D) is divided by the dose rate (R) at the time of entry to give D/R, i.e., $25/45=0.55$. This result falls between two values in the left-hand column of Table 12.64, and the smaller one is taken. Follow the $D/R=0.5$ line horizontally until the column headed "8 hours" after the detonation is reached. The allowable stay time is seen to be 31 minutes; for $D/R=0.6$, the corresponding time is 38 minutes, and so the actual permissible stay time would be about 34 minutes. By using both Tables 12.63 and 12.64, a variety of other estimates can be made.

12.65 There are two important reservations which must be kept in mind in using Tables 12.63 and 12.64. First, if there is any change in the situation, either by further contamination or by decontamination in the period between the two times concerned, the results will not be valid. Second, even if the conditions under which the tables are applicable are fulfilled, the estimates should be used for *planning purposes only*, and to provide a guide for any action that may be required. Changes in dose rates and total accumulated doses over a period of time must always be checked by instruments.

Food and Water

12.66 After a nuclear attack, in addition to protection from external residual radiation exposure, it is important that personnel in the fallout area also be protected from internal radiation exposure due to ingestion of radioactive fallout material along with food and water. Food and water are not adversely affected by exposure to the residual radioactivity. The principle of protection to be understood is that fallout material must be removed from food and water prior to consumption to prevent this material from getting inside the body. Relative to that which could be taken into the body by eating and drinking, it appears that the amount of radioactive material taken in by inhalation may be small (see §11.160). Nevertheless, air which contains fallout particles should not be directly inhaled without a protective respiratory device (such as a dust-filter respirator) until it is established by monitoring procedures that the air is free from radioactive contamination.

12.67 The contamination of emergency food and water supplies by residual radiation can be prevented by storing them in dust-tight containers. Although the outside of a container may become contaminated by fallout, most of the radioactive substance can be removed by washing the container before it is opened. The foods or

fluids can then be removed and consumed without significant contamination.

12.68 If emergency food supplies do become contaminated, or if it is necessary to resort to contaminated sources after emergency supplies are exhausted, many types of food can be treated to remove the radioactive material. Fresh fruits and vegetables can be washed or peeled to remove the outer skin or leaves. Food products of the absorbent type cannot be decontaminated in this manner and should be disposed of by burial. Boiling or cooking of the food has no effect in removing the fallout material. Milk, from cows which survive in a heavily contaminated area, may not be safe to drink because of the radioiodine content and this condition may persist for weeks or months.

12.69 Domestic water supplies from underground sources will usually remain free from radioactive contamination. Water supplies from surface sources may become contaminated if watersheds and open reservoirs are in areas of heavy fallout. However, most of the radioactive fallout material would be removed by regular water treatment which includes coagulation, sedimentation, and filtration. If a surface water supply is not treated in this manner, but merely chlorinated, it may be unfit for consumption for several days after an attack. As a result of dilution and natural decay the contamination will decrease with time.

12.70 If the regular water supply is not usually subjected to any treatment other than chlorination, and an alternative source is not available, consideration should be given in advance planning to the provision of ion-exchange columns or beds for emergency decontamination use. Home water softeners might serve the same purpose on a small scale. The water contained in a residential hot-water heater would serve as an emergency supply, provided it can be removed without admitting contaminated water. Water may also be distilled to make it safe for drinking purposes. *It should be emphasized that mere boiling of water contaminated with fallout is of absolutely no value in removal of the radioactivity.*

Decontamination

12.71 Decontamination is the process of removing radioactive material from a location where it is a hazard to one in which it can do little or no harm. It is one of the means which are available for reducing the radiation dose that would be received from fallout. Pref-

erably it should be accomplished under the supervision of personnel trained in decontamination procedures. Radiation measuring instruments should be used not only to determine the effectiveness of the decontamination but also to make sure that the contaminated material is disposed of in a safe manner.

12.72 Because of its particulate nature, fallout will tend to collect on horizontal surfaces, e.g., roofs, streets, tops of vehicles, and the ground. In the preliminary decontamination, therefore, the main effort should be directed toward cleaning such surfaces. The simplest way of achieving this is by water washing, if an adequate supply of water is available. The addition of a commercial wetting agent (detergent) will make the washing more efficient. The radioactive material is thus tranferred to storm sewers where it is less of a hazard. Covering the ground around a building with uncontaminated earth or removing the top layer of the ground to a distance, by means of earth-moving equipment, are methods for reducing the dose rate inside a building. Inasmuch as decontamination of streets, buildings, and other large items requires substantial manpower and resources, the effectiveness of these operations will benefit from sound planning and skilled supervision.

12.73 It is important to note, in connection with removal of contaminated earth for the purpose described above or to provide a means of transit, that the gamma rays from fission products can travel considerable distances through air. For example, at 3 feet above the ground, roughly 50 percent of the dose rate received in the center of a large, flat, uniformly contaminated area comes from distances greater than 50 feet away, and about 25 percent from distances more than 200 feet away. Thus, complete removal of the contaminated surface from a circle 200 feet in radius would reduce the dose rate in the center to about one-fourth of its original value. However, if the contaminated earth were not completely removed, but just pushed to the outside of the circle, the dose rate would be considerably greater than one-fourth the initial value.

12.74 It is apparent, therefore, that if facilities are to be provided across open country which is contaminated over a large area, bulldozing the top few inches of contaminated soil to the sides will be satisfactory only if a wide strip is cleared. Thus, if the strip is 250 feet in width, the radiation dose rate in the middle will be reduced to one-tenth of the value before clearing. A similar result may be achieved by scraping off the top layer of soil and burying it under fresh soil. Something like a foot of earth cover would be required to decrease the dose rate by a factor of ten.

722-454 O - 64 - 43

12.75 Badly contaminated clothing, as well as rugs, curtains, and upholstered furniture, would have to be discarded and buried or stored in an isolated location. When the radioactivity has decayed to a sufficient extent, or if the initial contamination is not too serious, laundering may be effective in reducing the activity of clothing and fabrics, to permit their recovery. Thorough vacuum cleaning of furniture might be adequate in some cases, but an instrument check would be necessary before further use.

SUMMARY

Planning Protection

12.76 In planning protection against the hazards associated with a nuclear attack, it must be recognized that the amount of protection that will be available to individuals is, in a large degree, directly related to the extent of public knowledge concerning nuclear weapons effects and associated protective measures, and to the steps taken prior to the attack to put these measures into a state of readiness. There are certain actions which can be taken by the unprepared in extreme emergencies, but the protection achieved is minor when compared to that which would be available to those who had made adequate preparations. Moreover, following an attack there are certain procedures that can tend to minimize the remaining hazards and these also will be made more effective by sufficient concern beforehand as to their implementation.

12.77 A massive, reinforced, fireproof shelter structure is required at close distances to protect individuals against the severe immediate effects (blast, thermal, and initial nuclear radiation) of a nuclear explosion. This type of protection is the most comprehensive and requires the greatest amount of preplanning effort and knowledge of the effects hazards. Conventional buildings may also be designed to be blast and fire resistant. Measures to minimize the thermal and fire hazard (§ 12.39 *et seq.*) may also be effected. In those areas where early fallout is expected to be a hazard, shelters may be constructed and provision made for occupying them for considerable lengths of time. Knowledge of warning systems and evacuation procedures will also minimize confusion. Moreover, possession of battery operated communications systems and of radiation monitoring equipment will make it possible to obtain information on the condition of the occupied area following an attack.

12.78 In the event that shelters are not available, certain evasive actions may prove helpful at distances where the immediate effects are least severe. By instantly falling prone and covering exposed portions of the body or getting behind opaque objects, much of the thermal radiation may be avoided, especially in the case of large-yield weapons. Under no circumstances should an individual look in the direction of the fireball. Staying behind thick walls or lying in a deep ditch may help to avoid initial nuclear radiation. All of the above actions will also help to decrease the possible danger from the blast wave. Moreover, persons should avoid areas which have frangible materials, such as window glass, plaster, etc., which may become flying debris by the action of the blast.

12.79 After the immediate effects of the nuclear explosion are over, certain acts are required to minimize the hazards of the early fallout and from the fires which may result from thermal radiation and secondary blast effects. First, if small fires can be quickly extinguished, extensive conflagrations may be prevented. This must be accomplished before the arrival of the fallout or in areas of low radioactivity levels. Some protection from the fallout may be secured in the basements of buildings or in a quickly constructed shelter, such as is described in § 12.55. It is important to keep from coming into physical contact with the fallout particles, and to prevent contamination of food and water sources. Monitoring equipment should be used to determine areas which have safe radiation levels and decontamination efforts can proceed to recover necessary equipment, buildings, and areas.

Conclusion

12.80 Much of the discussion presented in earlier sections of this chapter have been based, for simplicity, on the effects of a single weapon. It must not be overlooked that in a nuclear attack some areas may be subjected to several bursts. The basic principles of protection would remain unchanged, but protective action against *all* the effects of a nuclear explosion—blast, thermal radiation, initial nuclear radiation, and fallout—would become even more important. There is a good possibility that many people would survive a nuclear attack and this possibility would be greatly enhanced by utilizing the principles of protection in preattack preparations and planning, in taking evasive action at the time of an attack, and in determining what should be done in the recovery phase after the attack.

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*These publications may be obtained for a small charge from the Office of Technical Services, U.S. Department of Commerce, Washington, D.C.

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*These publications may be obtained for a small charge from the Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C.

APPENDIX A

NUCLEAR WEAPONS SAFETY AND ACCIDENT HAZARDS

Introduction

A.1 Nuclear weapons are designed with great care to explode only when deliberately armed and fired. Nevertheless, there is always a possibility that, as a result of accidental circumstances, an explosion will take place inadvertently. Although all conceivable precautions are taken to prevent them, such accidents might occur in areas where the weapons are assembled and stored, during the course of loading and transportation on the ground, or when actually in the delivery vehicle, e.g., an airplane or a missile.

A.2 In general, nuclear weapons contain varying amounts of high explosive (§ 1.54), in addition to the fissionable material, i.e., the nuclear explosive. The chances that the latter alone will detonate are so remote that they can be ruled out completely. It is the high-explosive component which comprises the main possible hazard, just as it does with conventional weapons. The spontaneous detonation of this material, without external cause, is highly improbable, but an explosion might occur if the weapon were dropped from a height or if it were involved in a fire. Both aircraft and missiles contain fuel or propellant which is combustible and so in an accident to these vehicles a serious fire could develop which might possibly, although by no means certainly, cause the detonation of the high explosive in a nuclear weapon.

A.3 Even if such an explosion did occur, the nuclear component would not necessarily be affected. A nuclear weapon is a complex system and all of its components must function almost perfectly if it is to produce an energy release that even approaches the design value. Any nuclear energy contribution resulting from the accidental detonation of the high-explosive component will, therefore, be either completely absent or very small. During more than 16 years (from 1945 through 1961) of storing, transporting, flying, overhauling, modifying, inspecting, and otherwise working on and with nuclear

weapons, the nuclear part of the weapon has not contributed to the cause or the effect of an accident. Although any accident is to be deplored, the fact that none has been more serious than from a conventional high-explosive weapon of moderate power, is a tribute to the extreme care devoted to the design of nuclear weapons and to the development of safe procedures for handling and transporting them.

A.4 Before discussing the various hazards which might be associated with an accident to a nuclear weapon, mention may be made of the possibility of a nuclear explosion being produced deliberately by sabotage or by the action of a psychotic individual who has access to a weapon. To eliminate or, at least, to minimize the probability of such an occurrence, there are positive physical and procedural measures which prevent deliberate or inadvertent arming, launching, firing, or release of a nuclear weapon. Among the precautions taken mention may be made of the use of launch or release controls which are locked or sealed in the safe position, the employment of two or more separate controls, and procedures requiring the presence of two or more properly informed and authorized persons.

A.5 Since accidents, by their very nature, are completely unpredictable, consideration must be given to all conceivable hazards that might arise in the storage or transportation of nuclear weapons. These hazards may be due to (*a*) fire and detonation of the high explosive, (*b*) fissionable material, i.e., uranium and plutonium, (*c*) tritium, which is radioactive, and (*d*) fission products in the unlikely event that there is an appreciable nuclear yield. These aspects of accidents to nuclear weapons will be considered in turn.

Fire and Detonation

A.6 If a nuclear weapon is exposed to the flames from a gasoline or similar fire, arising from the fuel or propellant of the carrying vehicle, the high explosive will probably ignite and burn. Fires resulting from large quantities of burning high explosives are very difficult to extinguish. At the same time, acrid, suffocating, and toxic gases are produced, and a poisonous residue may remain. If the high explosive is confined, as in an intact weapon, detonation may occur at any time. In addition, high explosives melt at relatively low temperatures; the heat of the fire may thus cause the molten explosive to flow out of the weapon and then resolidify. In this state, the material is extremely sensitive to shock, and may detonate if stepped on.

A.7 In any accident involving a nuclear weapon, such as dropping or exposure to fire, there is a possibility that detonation of the high explosive may occur. However, one of the characteristics of TNT and similar explosives is the unpredictability of their response to a given stimulus. Thus, impact or a fire may or may not cause a detonation. If a detonation does occur, it can range from a very small to a large chemical explosion or it may be a series of small explosions. The breakage of a weapon due to impact or to a small explosion will probably result in scattering of small pieces of high explosive; these may burn and possibly explode.

A.8 Rough handling of high explosives as well as accidents can lead to the formation of powdered explosive. Under these conditions, most explosive materials are more unstable than in bulk form and are more apt to be detonated by shock or change in temperature. Exposure to sunlight also increases the sensitivity of high explosives; at the same time there is a change in color which makes small pieces and powder difficult to distinguish from their surroundings. The danger of an explosion is thereby increased.

A.9 The detonation of high explosives can cause injury to personnel by direct and indirect blast effects, as described in Chapter XI. The greatest danger is probably from flying debris, falling objects, fragments of glass, etc. It is recommended that, in the event of a nuclear weapon becoming involved in a fire, all persons not essential for damage control or recovery operation withdraw to a distance of at least 1,500 feet. This will minimize the injury potential of the blast that would result from the detonation of the high explosive.

A.10 Because of the formation of noxious fumes, etc., as stated above, produced by the burning explosive, and by any vehicle fuel that may be present, only those individuals properly protected with respiratory equipment should be permitted to remain in the downwind path of a fire or potential detonation. Smoke may be tolerated for a short period of time if necessary in the interest of saving lives. When the fire has subsided and a check has been made by instruments that no radiation hazard exists, trained experts may approach the scene of the accident in order to clear the area of scattered pieces of high explosive.

Fissionable Material

A.11 All nuclear weapons contain a certain amount of fissionable material, either uranium or plutonium (or both); these substances are radioactive, emitting alpha particles (§ 9.40). Following an accident

to a nuclear weapon, the fissionable material could, in some circumstances, be spread over a large area. However, because alpha particles cannot penetrate even the dead surface layer of the unbroken skin, the only possible hazard that could arise would be the entry of uranium or plutonium into the body. The danger from plutonium lies in the tendency of this element to concentrate in the bone, where the continuous emission of alpha particles may cause significant injury. Uranium, on the other hand, acts mainly as a chemical poison, and fairly large amounts would have to be absorbed to produce any serious effect. Both uranium and plutonium can be detected as surface contamination by instruments which indicate the presence of alpha particles; the particles from plutonium have the higher energies.

A.12 Plutonium and uranium react readily with oxygen from the air and so they may become dispersed as small particles of oxide if the fissionable material is exposed. This may occur if the nuclear weapon is broken by impact or by the detonation of the high explosive. In the event of a fire, very fine particles of the oxides may be carried in the smoke. In the few instances in which aircraft containing nuclear weapons have burned, the fissionable material melted and was left on the ground as a slag. In this condition, oxides will form on the surface and may become airborne if disturbed, e.g., by the wind, to become an inhalation hazard.

A.13 As is the case with fallout particles (§ 11.156), significant entry of plutonium and uranium oxides into the body can occur through the respiratory tract; even then, the nose and lungs act as effective filters. Because of their small solubility, absorption of the oxides by the gastrointestinal system is very low. Furthermore, pentration of intact skin is impossible and although the material may enter where the skin is broken, it will be localized at the point of access. It may then be cleansed away, even at some later time, without appreciable translocation to the blood stream or other body tissues having occurred.

A.14 The results of observations made at the Nevada Test Site indicate that, at distances greater than 1,500 feet from the incident, the amounts of plutonium that might be received either from a contaminated smoke cloud or in other ways would not exceed the accepted Radioactivity Concentration Guide values (§ 11.100). For undisturbed surfaces, initial concentrations up to 100 micrograms of plutonium per square foot appear to be tolerable; for uranium the tolerance value is somewhat higher. The general conclusion drawn from the tests is that, even though the Radioactivity Concentration Guide for the body burden of plutonium is small (approximately half

a microgram), it is difficult to acquire this amount as a result of a weapon accident outside the exclusion radius given above. The permissible concentration of uranium in the body is larger than for plutonium, and is not likely to be attained in the same circumstances.

Tritium

A.15 Tritium is another radioactive isotope used in weapons which could be hazardous in a confined area. In air tritium becomes an analogue of water, i.e., T_2O or HTO. In an enclosed space where the tritium water vapor can concentrate in the air, it can be easily absorbed through the unbroken skin, the lungs, and the gastrointestinal system, constituting an exposure problem to the entire body. Should it enter the body, tritium water dissolves in the body water and is eliminated at the same rate as ordinary water since it does not tend to concentrate in bone or in any organ as do some of the more hazardous radioactive materials.

A.16 From the point of view of the general public, the possibility of confrontation with a tritium hazard is negligible, for only selected military personnel can gain access to areas of enclosure which contain nuclear weapons. Because the existence of tritium in air can be detected by instruments sensitive to beta particles, monitoring systems are installed wherever necessary. The precautionary procedures employed to protect against the possible hazards from other radioactive materials in weapons provide more than adequate safeguards against tritium. The accepted Radioactivity Concentration Guide for this isotope is 3 millicuries distributed throughout the body. To accumulate such a dose it would be necessary to breathe for an hour air containing a concentration of 21 millicuries per cubic foot.

Fission Products

A.17 Fission products would be produced in an accident with a nuclear weapon only if there were a nuclear (fission) contribution to the energy released in a fire or explosion. The probability that there will be any nuclear yield at all is extremely small, but the possibility must, of course, be kept in mind. In no accident, to date, has there been any fission product release, although in some cases the weapon has become hot enough to cause the fissionable material to melt, as noted earlier.

A.18 If there should be any nuclear yield, the hazard would be mainly due to the beta particles and gamma rays emitted by the radio-

active fission products. The effects would be similar to those arising from the residual nuclear radiation, as described in Chapter IX, but scaled down to the actual fission yield in the accident. In addition, neutrons released in the fission process may be captured by materials close to the explosion and so produce induced activity (§ 9.31), consisting of either beta particles alone or in conjunction with gamma rays. Both beta and gamma radiation are easily detected with the proper instruments, so that survey of an accident area will readily indicate if a fission energy release has occurred. If it has, then proper precautions must be taken in cleaning up the area. Incidentally, if the beta-gamma survey meter shows the presence of contamination, it may be taken for granted, without further test, that fissionable material (uranium or plutonium) is also present. As a general rule, it is expected that the radiation dose from fission products and induced activity delivered at a distance of 1,500 feet from the scene of the accident will be negligible.

Protective Measures

A.19 The Department of Defense and the Atomic Energy Commission have several hundred teams of men, in various parts of the United States, who are trained to deal with accidents involving nuclear weapons. Since such an accident may occur anywhere, for example, as the result of the crash of an airplane carrying a weapon, it is imperative that fire, police, civil defense, public health authorities, and other emergency services should take appropriate action. If it appears at all practicable, the first step should be to rescue and assist injured personnel. Next, the nearest military installation or AEC office should be notified of the accident, so that a special team may be dispatched to the scene. At the same time advice may be obtained concerning further action. Meanwhile, the area surrounding the accident should be cleared of all non-essential personnel to a distance of at least 1,500 feet.

A.20 If there is a fire and it is apparent that the weapon is not burning or engulfed in flames, an attempt should be made to extinguish the fire with water, in the normal manner, from the upwind side only. If the water seems to accelerate the burning, then it must be stopped. The weapon should be kept cool by means of a water spray, since it is expected that the high explosive will not detonate if its temperature is maintained below 300° F. In cases where the weapon is not in the fire, the foam used for extinguishing fuel fires can be spread over the weapon to protect it from radiated heat from flames. The breaking

down of a foam blanket on fuel with water streams must be avoided.

A.21 If the weapon is engulfed in flames or it is believed that the high explosive is burning, no attempt should be made to put out the fire. All personnel should then evacuate the area of 1,500 feet radius around the site of the accident because of the danger of detonation occurring. It may be mentioned that burning high explosive may sometimes be detected by jets of white flame coming out of the weapon ("torching"), but this is not always observed. Consequently, if the flames, such as those produced by burning fuel, appear to be growing in intensity and extending toward or actually enveloping the weapon, all personnel should be removed from the scene.

A.22 The area downwind from the accident should be kept clear in order to avoid the toxic, and possibly radioactive, smoke from a burning weapon. If exposure to dense smoke is necessary for any length of time, dust-filtering masks and goggles, or special breathing apparatus, should be used. But the lack of such equipment should not hold up rescue efforts which require a short stay in the smoke area. Personnel who have been exposed to smoke must be monitored for radioactivity and, if necessary, decontaminated by members of the special team trained for the work. In fact, such action is advisable for all personnel who may have been contaminated in any way. They should be prevented from wandering about, since this would spread the radioactivity and make it more difficult to clear up.

A.23 If the special team has not arrived by the time the fire has subsided or been extinguished, no attempt should be made to clean up the scene of the accident. It may be highly radioactive and could represent a serious radiation hazard. For the same reason, the area of the accident should be roped off so as to prevent access by anyone, other than members of the survey teams. After they have made a careful examination of the area, they will either undertake its decontamination or will advise on what should be done in the interests of safety and security.

APPENDIX B

ANNOUNCED NUCLEAR DETONATIONS

This appendix contains information concerning all announced nuclear detonations carried out by the United States, the U.S.S.R., the United Kingdom, and the Republic of France prior to January 1964.

The dates and times given in the list of U.S. shots are Greenwich Civil Time (GCT). The heights of burst are heights above the surface; the heights of the cloud and tropopause refer to mean sea level (MSL). The abbreviations T, KT, and MT are used to express the explosion yields in tons, kilotons (1,000 tons), and megatons (1,000,000 tons) TNT equivalent, respectively. The term "nominal" implies a yield of approximately 20 kilotons TNT equivalent.

The approximate latitudes and longitudes of the various test sites are as follows:

UNITED STATES	
Nevada Test Site, U.S.A.	37° N. 116° W.
Eniwetok Proving Grounds, Pacific:	
Eniwetok	11° N. 162° E.
Bikini	11° N. 165° E.
Johnston Island, Pacific	17° N. 169° W.
Christmas Island, Pacific	2° N. 157° W.
UNITED KINGDOM	
Monte Bello Islands, Australia	20° S. 115° E.
Woomera, Australia	31° S. 137° E.
Maralinga Proving Ground, Australia	30° S. 131° E.
Christmas Island, Pacific	2° N. 157° W.
Nevada Test Site, U.S.A.	37° N. 116° W.
U.S.S.R.	
Arctic Test Site	75° N. 55° E. (Novaya Zemlya).
Siberian Test Site	52° N. 78° E.
U.S.S.R	Denotes the explosion was in Soviet territory, but the test site was not identified.
REPUBLIC OF FRANCE	
Reggan, Algeria	27° N. 0°.
In Ekker, Algeria	24° N. 5° E.

ANNOUNCED UNITED STATES NUCLEAR DETONATIONS

Name	Date (GCT)	Time (GCT)	Location of Shot	Height of Burst (Feet)	Type of Burst	Mean Sea Level (Feet)			Yield	Remarks
						Cloud Top	Cloud Base	Tropopause		
TRINITY:										
Trinity	16/7/45	1230	Alamogordo, N.M.	100	Tower	35,000			19 KT	First test of an A-bomb.
WORLD WAR II	5/8/45	2315	Hiroshima, Japan	~1,850	Air				Nominal	First combat use.
	9/8/45	0158	Nagasaki, Japan	~1,850	Air				Nominal	Second combat use.
CROSSROADS:										
Able	30/6/46	2201	Bikini	520	Air	35,000			Nominal	
Baker	24/7/46	2135	Bikini	−90	UW	8,000			Nominal	
SANDSTONE:										
X-ray	14/4/48	1817	Eniwetok	200	Tower	56,000	25,000	56,000	37 KT	
Yoke	30/4/48	1809	Eniwetok	200	Tower	55,000	35,000	54,000	49 KT	
Zebra	14/5/48	1804	Eniwetok	200	Tower	28,000	20,000	54,000	18 KT	
RANGER:										
Able	27/1/51	1345	Nevada	1,060	Air	17,000		33,000	1 KT	
Baker	28/1/51	1352	Nevada	1,080	Air	35,000		32,000	8 KT	
Easy	1/2/51	1347	Nevada	1,080	Air	12,000		35,000	1 KT	
Baker-2	2/2/51	1349	Nevada	1,100	Air	36,000		38,000	8 KT	
Fox	6/2/51	1347	Nevada	1,435	Air	42,000		40,000	22 KT	
GREENHOUSE:										
Dog	7/4/51	1834	Eniwetok	300	Tower			55,000		
Easy	20/4/51	1827	Eniwetok	300	Tower	40,000	30,000	54,000	47 KT	
George	8/5/51	2130	Eniwetok	200	Tower			55,000		
Item	24/5/51	1817	Eniwetok	200	Tower			55,000		
BUSTER-JANGLE:										
Able	22/10/51	1400	Nevada	100	Tower	8,000	6,700		$<$0.1 KT	
Baker	28/10/51	1520	Nevada	1,118	Air	29,000	23,000	39,000	3.5 KT	
Charlie	30/10/51	1500	Nevada	1,132	Air	40,000	32,000	38,000	14 KT	
Dog	1/11/51	1530	Nevada	1,417	Air	40,000	27,000	38,000	21 KT	
Easy	5/11/51	1630	Nevada	1,314	Air	45,000	31,000	35,000	31 KT	
Sugar	19/11/51	1700	Nevada	4	Surface	16,000	11,000		1.2 KT	
Uncle	29/11/51	2000	Nevada	−17	UG	11,000			1.2 KT	

TUMBLER-SNAPPER:										
Able	1/4/52	1700	Nevada	793	Air	16,000		42,000	1 KT	
Baker	15/4/52	1730	Nevada	1,050	Air	16,000	10,000	38,000	1 KT	
Charlie	22/4/52	1730	Nevada	3,447	Air	42,000	31,000	38,000	31 KT	
Dog	1/5/52	1630	Nevada	1,040	Air	42,000	28,000	38,000	19 KT	
Easy	7/5/52	1215	Nevada	300	Tower	34,000		41,000	12 KT	
Fox	25/5/52	1200	Nevada	300	Tower	41,000		37,000	11 KT	
George	1/6/52	1155	Nevada	300	Tower	37,000		37,000	15 KT	
How	5/6/52	1155	Nevada	300	Tower	41,000		40,000	14 KT	
IVY:										
Mike	31/10/52	1915	Eniwetok		Surface	~100,000		56,000	10.4 MT	Experimental thermonuclear device.
King	15/11/52	2330	Eniwetok	1,480	Air	~70,000		55,000	High yield	
UPSHOT-KNOTHOLE:										
Annie	17/3/53	1320	Nevada	300	Tower	41,000	28,000	36,000	16 KT	
Nancy	24/3/53	1310	Nevada	300	Tower	42,000	26,000	40,000	24 KT	
Ruth	31/3/53	1300	Nevada	300	Tower	14,000	11,000	36,000	0.2 KT	
Dixie	6/4/53	1530	Nevada	6,020	Air	43,000	33,000	36,000	11 KT	
Ray	11/4/53	1245	Nevada	100	Tower	13,000	8,000	38,000	0.2 KT	
Badger	18/4/53	1235	Nevada	300	Tower	35,000	23,000	39,000	23 KT	
Simon	25/4/53	1230	Nevada	300	Tower	45,000	31,000	38,000	43 KT	
Encore	8/5/53	1530	Nevada	2,425	Air	41,000	29,000	39,000	27 KT	
Harry	19/5/53	1205	Nevada	300	Tower	43,000	27,000	42,000	32 KT	
Grable	25/5/53	1530	Nevada	524	Gun	38,000	23,000	38,000	15 KT	Fired from 280 mm gun.
Climax	4/6/53	1115	Nevada	1,334	Air	43,000	35,000	39,000	61 KT	
CASTLE:										
Bravo	28/2/54	1845	Bikini		Surface	114,000	55,000	55,000	15 MT	Experimental thermonuclear device.
Romeo	26/3/54	1830	Bikini		Barge			55,000		
Koon	6/4/54	1820	Bikini		Surface			53,000	~100 KT	
Union	25/4/54	1810	Bikini		Barge			57,000		
Yankee	4/5/54	1810	Bikini		Barge			55,000		
Nectar	13/5/54	1820	Eniwetok		Barge			56,000		
TEAPOT:										
Wasp	18/2/55	2000	Nevada	762	Air	22,000	15,000		1 KT	
Moth	22/2/55	1345	Nevada	300	Tower	25,000	16,000		2 KT	
Tesla	1/3/55	1330	Nevada	300	Tower	30,000	18,000	38,000	7 KT	
Turk	7/3/55	1320	Nevada	500	Tower	44,000	36,000	40,000	43 KT	
Hornet	12/3/55	1320	Nevada	300	Tower	35,000	27,000	38,000	4 KT	
Bee	22/3/55	1305	Nevada	500	Tower	40,000	29,000	37,000	8 KT	
Ess	23/3/55	2030	Nevada	-67	UG	12,000		39,000	1 KT	

ANNOUNCED UNITED STATES NUCLEAR DETONATIONS—Continued

Name	Date (GCT)	Time (GCT)	Location of Shot	Height of Burst (Feet)	Type of Burst	Mean Sea Level (Feet)			Yield	Remarks
						Cloud Top	Cloud Base	Tropo-pause		
TEAPOT—Continued										
Apple-1	29/3/55	1255	Nevada	500	Tower	32,000	22,000	39,000	14 KT	
Wasp Prime	29/3/55	1800	Nevada	740	Air	32,000		40,000	3 KT	
HA	6/4/55	1800	Nevada	36,620 (MSL)	Air	55,000		31,000	3 KT	
Post	9/4/55	1230	Nevada	300	Tower	16,000	13,000		2 KT	
Met	15/4/55	1915	Nevada	400	Tower	40,000	31,000	37,000	22 KT	
Apple-2	5/5/55	1210	Nevada	500	Tower	43,000	34,000	41,000	29 KT	
Zucchini	15/5/55	1200	Nevada	500	Tower	35,000	25,000	44,000	28 KT	
WIGWAM:										
Wigwam	14/5/55	2000	29° N. 126° W	−2,000	UW				30 KT	
REDWING:										
Lacrosse	4/5/56	1825	Eniwetok		Surface			53,000		Kiloton range.
Cherokee	20/5/56	1751	Bikini	4,320	Air			53,000		Several megatons. First air drop by U.S. of a thermonuclear weapon.
Zuni	27/5/56	1756	Bikini		Surface			51,000		
Erie	30/5/56	1815	Eniwetok	300	Tower			54,000		
Seminole	6/6/56	0055	Eniwetok		Surface			52,000		
Flathead	11/6/56	1826	Bikini		Barge			50,000		
Blackfoot	11/6/56	1826	Eniwetok	200	Tower			52,000		
Osage	16/6/56	0114	Eniwetok	680	Air			52,000		
Dakota	25/6/56	1806	Bikini		Barge			54,000		
Apache	8/7/56	1806	Eniwetok		Barge			52,000		
Navajo	10/7/56	1756	Bikini		Barge			50,000		
Tewa	20/7/56	1748	Bikini		Barge			52,000		
Huron	21/7/56	1816	Eniwetok		Barge			51,000		

PLUMBBOB:										
Boltzmann	28/5/57	1155	Nevada	500	Tower	33,000	23,000	41,000	12 KT	
Franklin	2/6/57	1155	Nevada	300	Tower	17,000	14,000		140 T	
Lassen	5/6/57	1145	Nevada	500	Balloon	7,000		43,000	0.5 T	
Wilson	18/6/57	1145	Nevada	500	Balloon	35,000	25,000	40,000	10 KT	
Priscilla	24/6/57	1330	Nevada	700	Balloon	43,000	24,000	49,000	37 KT	
Hood	5/7/57	1140	Nevada	1,500	Balloon	48,000	35,000	53,000	74 KT	
Diablo	15/7/57	1130	Nevada	500	Tower	32,000	20,000	43,000	17 KT	
John	19/7/57	1400	Nevada	20,000	Rocket	44,000		48,000	~2 KT	
Kepler	24/7/57	1150	Nevada	500	Tower	28,000	20,000	34,000	10 KT	
Owens	25/7/57	1330	Nevada	500	Balloon	35,000	20,000	49,000	9.7 KT	
Stokes	7/8/57	1225	Nevada	1,500	Balloon	37,000	27,000	47,000	19 KT	
Shasta	18/8/57	1200	Nevada	500	Tower	32,000	16,000	50,000	17 KT	
Doppler	23/8/57	1230	Nevada	1,500	Balloon	38,000	23,000	43,000	11 KT	
Franklin Prime	30/8/57	1240	Nevada	750	Balloon	32,000	21,000	32,000	4.7 KT	
Smoky	31/8/57	1230	Nevada	700	Tower	38,000		35,000	44 KT	
Galileo	2/9/57	1240	Nevada	500	Tower	37,000	17,000	39,000	11 KT	
Wheeler	6/9/57	1245	Nevada	500	Balloon	17,000	14,000	50,000	197 T	
Laplace	8/9/57	1300	Nevada	750	Balloon	20,000	14,000	44,000	1 KT	
Fizeau	14/9/57	1645	Nevada	500	Tower	40,000	27,000	43,000	11 KT	
Newton	16/9/57	1250	Nevada	1,500	Balloon	32,000	19,000	52,000	12 KT	
Rainier	19/9/57	1700	Nevada	−790	UG				1.7 KT	There was no tunnel venting.
Whitney	23/9/57	1230	Nevada	500	Tower	30,000	18,000	53,000	19 KT	
Charleston	28/9/57	1300	Nevada	1,500	Balloon	32,000	20,000	45,000	12 KT	
Morgan	7/10/57	1300	Nevada	500	Balloon	40,000	26,000	37,000	8 KT	
HARDTACK PHASE I:										
Yucca	28/4/58	0240	12° 37′ N., 163° 01′ E.	86,000	Balloon			53,000		
Cactus	5/5/58	1815	Eniwetok		Surface			51,000		
Fir	11/5/58	1750	Bikini		Barge			54,000		
Butternut	11/5/58	1815	Eniwetok		Barge			53,000		
Koa	12/5/58	1830	Eniwetok		Surface			57,000		
Wahoo	16/5/58	0130	Eniwetok	−500	UW			59,000		
Holly	20/5/58	1830	Eniwetok		Barge			52,000		
Nutmeg	21/5/58	2120	Bikini		Barge			54,000		
Yellowwood	26/5/58	0200	Eniwetok		Barge			55,000		
Magnolia	26/5/58	1800	Eniwetok		Barge			54,000		
Tobacco	30/5/58	0215	Eniwetok		Barge			55,000		
Sycamore	31/5/58	0300	Bikini		Barge			55,000		

ANNOUNCED UNITED STATES NUCLEAR DETONATIONS—Continued

Name	Date (GCT)	Time (GCT)	Location of Shot	Height of Burst (Feet)	Type of Burst	Mean Sea Level (Feet) Cloud Top	Cloud Base	Tropopause	Yield	Remarks
HARDTACK PHASE I—Continued										
Rose	2/6/58	1845	Eniwetok		Barge			57,000		
Umbrella	8/6/58	2315	Eniwetok	−150	UW			54,000		
Maple	10/6/58	1730	Bikini		Barge			53,000		
Aspen	14/6/58	1730	Bikini		Barge			52,000		
Walnut	14/6/58	1830	Eniwetok		Barge			54,000		
Linden	18/6/58	0300	Eniwetok		Barge			54,000		
Redwood	27/6/58	1730	Bikini		Barge			52,000		
Elder	27/6/58	1830	Eniwetok		Barge			52,000		
Oak	28/6/58	1930	Eniwetok		Barge			50,000		
Hickory	29/6/58	0000	Bikini		Barge			51,000		
Sequoia	1/7/58	1830	Eniwetok		Barge			52,000		
Cedar	2/7/58	1730	Bikini		Barge			51,000		
Dogwood	5/7/58	1830	Eniwetok		Barge			52,000		
Poplar	12/7/58	0330	Bikini		Barge			55,000		
Juniper	22/7/58	0420	Bikini		Barge			51,000		
Oliver	22/7/58	2030	Eniwetok		Barge			48,000		
Pine	26/7/58	2030	Eniwetok		Barge			52,000		
Teak	1/8/58	1050	Johnston Island	252,000	Rocket					Megaton range.
Orange	12/8/58	1030	Johnston Island	141,000	Rocket					Megaton range.
HARDTACK PHASE II:										
Eddy	19/9/58	1400	Nevada	500	Balloon	11,000	7,500	48,000	83 T	
Mora	29/9/58	1405	Nevada	1,500	Balloon	18,500	10,000	40,000	2 KT	
Tamalpais	8/10/58	2200	Nevada	−330	UG	Low diffuse cloud			72 T	Slight venting.
Quay	10/10/58	1430	Nevada	100	Tower	10,000	7,500		79 T	
Lea	13/10/58	1320	Nevada	1,500	Balloon	17,000	12,000		1.4 KT	
Hamilton	15/10/58	1600	Nevada	50	Tower	6,000	4,500		1.2 T	
Logan	16/10/58	0600	Nevada	−830	UG				5 KT	No venting.
Dona Ana	16/10/58	1420	Nevada	450	Balloon	11,000	6,500	49,000	37 T	

Rio Arriba	18/10/58	1425	Nevada	72. 5	Tower	13, 500	11, 000	----------	90 T	
Socorro	22/10/58	1330	Nevada	1, 450	Balloon	26, 000	20, 000	----------	6 KT	
Wrangell	22/10/58	1650	Nevada	1, 500	Balloon	10, 000	7, 000	----------	115 T	
Rushmore	22/10/58	2340	Nevada	500	Balloon	11, 500	----------	42, 000	188 T	
Sanford	26/10/58	1020	Nevada	1, 500	Balloon	26, 000	12, 500	----------	4. 9 KT	
De Baca	26/10/58	1600	Nevada	1, 500	Balloon	17, 500	10, 000	----------	2. 2 KT	
Evans	29/10/58	0000	Nevada	−848	UG	----------	----------	----------	55 T	Venting.
Humboldt	29/10/58	1445	Nevada	25	Tower	7, 500	6, 000	----------	7. 8 T	
Santa Fe	30/10/58	0300	Nevada	1, 500	Balloon	18, 000	13, 000	39, 000	1. 3 KT	
Blanca	30/10/58	1500	Nevada	−835	UG	7, 700	----------	----------	19 KT	Slight venting.
ARGUS:										
Argus I	27/8/58	----------	South Atlantic (38° S. 12° W.)	~300 miles	Rocket	----------	----------	----------	1 - 2 KT	
Argus II	30/8/58	----------	South Atlantic (50° S. 8° W.)	~300 miles	Rocket	----------	----------	----------	1 - 2 KT	
Argus III	6/9/58	----------	South Atlantic (50° S. 10° W.)	~300 miles	Rocket	----------	----------	----------	1 - 2 KT	

ANNOUNCED U.S. NUCLEAR DETONATIONS, 1961–63

NEVADA SERIES

Name	Date (GCT)	Time (GCT)	Depth[1] (feet)	Type	Medium	Depression[2] (Diam. & Depth, feet)	Yield[3] (KT)	Remarks
Antler	15/ 9/61	1700	1,319	Underground	Tuff	None	2.4	Tunnel.
Shrew	16/ 9/61	1945	322	Underground	Alluvium	None	Low	
Chena	10/10/61	1800	838	Underground	Tuff	None	Low	Tunnel.
Mink	29/10/61	1830	630	Underground	Alluvium	None	Low	
Fisher	3/12/61	2304	1,193	Underground	Alluvium	600; 14	13.5	
Mad	13/12/61	1800	594	Underground	Alluvium	None	0.43	
Ringtail	17/12/61	1635	1,191	Underground	Alluvium	778; 2.17	Low	
Feather	22/12/61	1630	812	Underground	Tuff	None	Low	Tunnel.
Stoat	9/ 1/62	1630	992	Underground	Alluvium	602; 7.1	4.5	
Agouti	18/ 1/62	1800	856	Underground	Alluvium	604; 40	5.9	
Dormouse	30/ 1/62	1800	1,191	Underground	Alluvium	547; 14.4	Low	
Stillwater	8/ 2/62	1800	625	Underground	Alluvium	406; 39	2.7	
Armadillo	9/ 2/62	1800	786	Underground	Alluvium	590; 29	6.6	
Hardhat	15/ 2/62	1800	943	Underground	Granite	None	5.9	
Chinchilla	19/ 2/62	1630	492	Underground	Alluvium	302; 27	1.8	
Codsaw	19/ 2/62	1750	696	Underground	Tuff	230; 11	Low	
Cimarron	23/ 2/62	1800	1,000	Underground	Alluvium	484; 34	11.2	
Platypus	24/ 2/62	1630	190	Underground	Alluvium	None	Low	
Danny Boy	5/ 3/62	1815	110	See remarks	Basalt		0.42	Cratering test; crater diam. 265 ft, depth 84 ft .
Ermine	6/ 3/62	1630	240	Underground	Alluvium	None	Low	
Brazos	8/ 3/62	1800	841	Uhderground	Alluvium	466; 31	7.6	
Hognose	15/ 3/62	1630	789	Underground	Alluvium	478; 65	Low	
Hoosic	28/ 3/62	1800	614	Underground	Tuff	294; 20	3	
Chinchilla II	31/ 3/62	1800	448	Underground	Alluvium	235; 11	Low	
Dormouse II	5/ 4/62	1800	856	Underground	Alluvium	538; 96	10	
Passaic	6/ 4/62	1800	764	Underground	Tuff	512; 63	Low	
Hudson	12/ 4/62	1800	480	Underground	Tuff	None	Low	
Platte	14/ 4/62	1800	560	Underground	Tuff	None	1.7	Tunnel.
Dead	21/ 4/62	1840	634	Underground	Tuff	256; 11	Low	

Black	27/ 4/62	1800	714	Underground	Tuff	408; 55	Low	
Paca	7/ 5/62	1933	848	Underground	Alluvium	484; 60	Low	
Aardvark	12/ 5/62	1900	1,424	Underground	Tuff	924; 72	38	
Eel	19/ 5/62	1500	714	Underground	Tuff	234; 11	Low	
White	25/ 5/62	1500	635	Underground	Tuff	490; 50	Low	
Raccoon	1/ 6/62	1700	539	Underground	Alluvium	314; 24	Low	
Packrat	6/ 6/62	1700	860	Underground	Alluvium	598; 44	Low	
Des Moines	13/ 6/62	2200	610	Underground	Tuff	None	Low	Tunnel.
Daman I	21/ 6/62	1700	854	Underground	Alluvium	556; 96	Low	
Haymaker	27/ 6/62	1800	1,340	Underground	Alluvium	974; 107	56	
Marshmallow	28/ 6/62	1700	900	Underground	Tuff	None	Low	Tunnel.
Sacramento	30/ 6/62	2130	500	Underground	Alluvium	356; 41	Low	
Little Feller II	7/ 7/62	1900		Surface		None	Low	Slightly above ground.
Johnny Boy	11/ 7/62	1645	2	Surface	Alluvium		0.5	Slightly below ground.
Merrimac	13/ 7/62	1600	1,356	Underground	Alluvium	662; 50	Low	
Small Boy	14/ 7/62	1830		Surface		None	Low	Slightly above ground.
Little Feller I	17/ 7/62	1700		Surface		None	Low	Slightly above ground. Troop participation.
Wichita	27/ 7/62	2100	493	Underground	Alluvium	390; 36	Low	
York	24/ 8/62	1500	744	Underground	Tuff	500; 80	Low	
Bobac	24/ 8/62	1700	675	Underground	Alluvium	425; 45	Low	
Hyrax	14/ 9/62	1710	720	Underground	Alluvium	474; 100	Low	
Peba	20/ 9/62	1700	793	Underground	Alluvium	400; 80	Low	
Allegheny	29/ 9/62	1700	692	Underground	Tuff	100; 10	Low	
Mississippi	5/10/62	1700	1,620	Underground	Tuff	425; 125	Intermediate	
Roanoke	12/10/62	1500	510	Underground	Tuff	80; 5	Low	
Bandicoot	19/10/62	1800	800	Underground	Alluvium	300; 100	Low	
Santee	27/10/62	1500	1,050	Underground	Alluvium	400; 20	Low	
Madison	12/12/62	1725	1,160	Underground	Tuff	None	Low	Tunnel.
Numbat	12/12/62	1745	775	Underground	Alluvium	500; 60	Low	
Casselman	8/ 2/63	1600	1,000	Underground	Alluvium	450; 75	Intermediate or less.	
Acushi	8/ 2/63	1830	856	Underground	Alluvium	300; 50	Intermediate or less.	
Carmel	21/ 2/63	1947	536	Underground	Alluvium	None	Low	
Gerbil	29/ 3/63	1549	925	Underground	Alluvium	555; 48	Low	
Ferret Prime	5/ 4/63	1752	792	Underground	Alluvium	400; 100	Low	
Stones	22/ 5/63	1540	1,289	Underground	Alluvium	850; 90	Intermediate	
Yuba	5/ 6/63	1700	796	Underground	Tuff	None	Low	
Hutia	6/ 6/63	1400	442	Underground	Alluvium	300; 20	Low	

ANNOUNCED U.S. NUCLEAR DETONATIONS, 1961–63—Continued

NEVADA SERIES—Continued

Name	Date (GCT)	Time (GCT)	Depth[1] (feet)	Type	Medium	Depression[2] (Diam. & Depth, feet)	Yield[3] (KT)	Remarks
Mataco	14/ 6/63	1410	642	Underground	Alluvium	300; 50	Low	
Kennebec	25/ 6/63	2300	740	Underground	Alluvium	200; 30	Low	
Pekan	12/ 8/63	2345	997	Underground	Alluvium	550; 60	Low	
Satsop	15/ 8/63	1300	738	Underground	Alluvium	300; 40	Low	
[4]	20/ 8/63							
Kohocton	23/ 8/63	1320	852	Underground	Alluvium	None	Low	
Antanum	13/ 9/63	1353	740	Underground	Alluvium	None	Low	
Bilby	13/ 9/63	1700	2,413	Underground	Tuff	1800; 80	$\sim$200	
Grunion	11/10/63	1400	856	Underground	Alluvium	550; 90	Low	
Clearwater	16/10/63	1700	1,798	Underground	Tuff	None	Intermediate	
Anchovy	14/11/63	1600	853	Underground	Alluvium	600; 65	Low	
Mustang	15/11/63	1500	544	Underground	Alluvium	125; 15	Low	
Greys	22/11/63	1730	988	Underground	Alluvium	470; 42	Low	
Sardine	4/12/63	1638	855	Underground	Alluvium	550; 50	Low	
Eagle	12/12/63	1602	541	Underground	Alluvium	440; 60	Low	

[1] Depth is distance to nearest point at the earth's surface.

[2] Depression is subsidence of earth into underground cavity, as distinguished from crater formed by throw-out of earth.

[3] Low yield means less than 20 kilotons; intermediate means 20 to 999 kilotons inclusive; low megaton means one to several megatons.

[4] For purposes of totaling announced detonations, add 23 undeground U.S. weapons-related tests at the Nevada Test Site as having been conducted between September 15, 1961, and August 20, 1963. No other data on the 23 tests are available for public use.

VELA UNIFORM SEISMIC DETONATION

Name	Date	Depth	Medium	Yield	Location	Remarks
Shoal	10/26/63	1,205	Granite	About 12 KT	Near Fallon, Nev.	Nuclear test detection-research experiment.

PACIFIC SERIES

Name	Date (GCT)	Time (GCT)	Location	Height	Type of burst	Yield [1]	Remarks
Adobe	25/ 4/62	1546	Christmas Island area		Air	Intermediate	
Aztec	27/ 4/62	1602	Christmas Island area		Air	Intermediate	
Arkansas	2/ 5/62	1802	Christmas Island area		Air	Low megaton	
Questa	4/ 5/62	1905	Christmas Island area		Air	Intermediate	
Frigate Bird	6/ 5/62	2330	Christmas Island area		Air		Warhead in missile launched from Polaris submarine.
Yukon	8/ 5/62	1801	Christmas Island area		Air	Intermediate	
Mesilla	9/ 5/62	1701	Christmas Island area		Air	Intermediate	
Muskegon	11/ 5/62	1537	Christmas Island area		Air	Intermediate	
Swordfish	11/ 5/62	2002	Eastern Pacific		UW	Low	Antisubmarine rocket (ASROC) system proof test.
Encino	12/ 5/62	1703	Christmas Island area		Air	Intermediate	
Swanee	14/ 5/62	1522	Christmas Island area		Air	Intermediate	
Chetco	19/ 5/62	1537	Christmas Island area		Air	Intermediate	
Tanana	25/ 5/62	1609	Christmas Island area		Air	Low	
Nambe	27/ 5/62	1703	Christmas Island area		Air	Intermediate	
Alma	8/ 6/62	1703	Christmas Island area		Air	Intermediate	
Truckee	9/ 6/62	1537	Christmas Island area		Air	Intermediate	
Yeso	10/ 6/62	1601	Christmas Island area		Air	Low megaton	
Harlem	12/ 6/62	1537	Christmas Island area		Air	Intermediate	
Rinconada	15/ 6/62	1601	Christmas Island area		Air	Intermediate	
Dulce	17/ 6/62	1601	Christmas Island area		Air	Intermediate	
Petit	19/ 6/62	1501	Christmas Island area		Air	Low	
Otowi	22/ 6/62	1601	Christmas Island area		Air	Intermediate	

PACIFIC SERIES—Continued

Name	Date (GCT)	Time (GCT)	Location	Height	Type of burst	Yield	Remarks
Bighorn	27/ 6/62	1519	Christmas Island area		Air	Megaton range	
Bluestone	30/ 6/62	1521	Christmas Island area		Air	Low megaton	
Starfish Prime	9/ 7/62	0900	Johnston Island area	400 km	High altitude	1.4 megatons	
Sunset	10/ 7/62	1633	Christmas Island area		Air	Intermediate	
Pamlico	11/ 7/62	1537	Christmas Island area		Air	Low megaton	
Androscoggin	2/10/62	1618	Johnston Island area		Air	Intermediate	
Bumping	6/10/62	1603	Johnston Island area		Air	Low	
Chama	18/10/62	1601	Johnston Island area		Air	Low megaton	
Checkmate	20/10/62	0830	Johnston Island area	Tens of km	High altitude	Low	
Bluegill Triple Prime	26/10/62	1000	Johnston Island area	Tens of km	High altitude	Submegaton	
Calamity	27/10/62	1546	Johnston Island area		Air	Intermediate	
Housatonic	30/10/62	1602	Johnston Island area		Air	Megaton range	
Kingfish	1/11/62	1210	Johnston Island area	Tens of km	High altitude	Submegaton	
Tightrope	4/11/62	0730	Johnston Island area	Tens of km	High altitude	Low	

PLOWSHARE NUCLEAR DETONATIONS[1]

Name	Date (GCT)	Time (GCT)	Depth (ft)	Medium	Yield	Location	Remarks
Gnome	10/12/61	1900	1, 184	Salt	3.1 KT	Near Carlsbad, N. Mex.	Multiple-purpose experiment; formed hemispheric cavity, 160–170 ft diameter, 60–80 ft high.
Sedan	6/7/62	1700	635	Alluvium	100 KT	Nevada Test Site	Excavation experiment; formed crater about 1,280 ft diameter, 320 ft max depth; displaced about 6.5 million cu yd or 10.4 million tons of earth.
Anacostia	27/11/62	1800	750	Tuff	Low	Nevada Test Site	Plowshare Device Development Test.
Kaweah	21/ 2/63	1947	750	Alluvium	Low	Nevada Test Site	Plowshare Device Development Test.
Tornillo	11/10/63	2100	500	Alluvium	Low	Nevada Test Site	Plowshare Device Development Test.

[1] For the development of peaceful uses of nuclear explosives.

SAFETY EXPERIMENTS

Since 1955, the U.S. Atomic Energy Commission has conducted a number of safety experiments at the Nevada Test Site to determine the safety of nuclear weapons in case of accident. The following list includes those experiments which resulted in a measurable nuclear yield.

Name	Date (GCT)	Time (GCT)	Location of Shot	Height of Burst (Feet)	Type of Burst	Mean Sea Level (Feet)			Yield	Remarks
						Cloud Top	Cloud Base	Tropopause		
1956	18/1/56	2130	Nevada		Surface					
PLUMBBOB:										
Pascal A	26/7/57	0800	Nevada		UG	6,000				Slight nuclear yield.
Coulomb B	6/9/57	2005	Nevada		Surface	18,000		50,000	0.3 KT	
1957:										
Pascal C	6/12/57	2015	Nevada		Vertical shaft					Slight yield.
Coulomb C	9/12/57	2000	Nevada		Surface				0.5 KT	
HARDTACK PHASE II:										
Otero	12/9/58	2000	Nevada	—480	UG	9,000			38 T	
Bernalillo	17/9/58	1930	Nevada	—456	UG	7,500	5,500		15T	
Luna	21/9/58	1900	Nevada	—484	UG	Low diffuse cloud			1.5 T	
Valencia	26/9/58	2000	Nevada	—484	UG	5,500			2 T	
Mars	28/9/58	0000	Nevada		UG	Low diffuse cloud			13 T	Shot vented through tunnel.
Hidalgo	5/10/58	1410	Nevada	377	Balloon	12,000	8,000		77 T	
Colfax	5/10/58	1615	Nevada	—350	UG	5,500	4,500		5.5 T	
Neptune	14/10/58	1800	Nevada	—98.5	UG	11,000			115 T	Shot vented.
Vesta	17/10/58	2300	Nevada		Surface	10,000			24 T	
Catron	24/10/58	1500	Nevada	72 5	Tower	8,500	5,000		21 T	
Juno	24/10/58	1601	Nevada		Surface	5,500			1.7 T	
Ceres	26/10/58	0400	Nevada	25	Tower	6,000			0.7 T	
Chavez	27/10/58	1430	Nevada	52.5	Tower	6,500			0.6 T	
Titania	30/10/58	2034	Nevada	25	Tower	6,000			0.2 T	

UNITED KINGDOM NUCLEAR DETONATIONS

Name	Date	Type of Burst	Yield	Location	Remarks
HURRICANE	3/10/52	Ship	Kiloton range	Monte Bello Islands	
TOTEM	14/10/53	Tower	Kiloton range	Woomera	Test held at Emu Field, 300 miles NW of Woomera.
	26/10/53	Tower	Kiloton range	Woomera	Test held at Emu Field, 300 miles NW of Woomera.
MOSAIC	16/5/56	Tower	Kiloton range	Monte Bello Islands	
	19/6/56	Tower	Kiloton range	Monte Bello Islands	
BUFFALO	27/9/56	Tower	Kiloton range	Maralinga	
	4/10/56	Surface	Low yield	Maralinga	
	11/10/56	Air	Low yield	Maralinga	First air drop
	22/10/56	Tower	Kiloton range	Maralinga	
GRAPPLE	15/5/57	Air	Megaton range	Christmas Island area	
	31/5/57	Air	Megtaon range	Christmas Island area	
	19/6/57	Air	Megaton range	Christmas Island area	
ANTLER	14/9/57	Tower	Low yield	Maralinga	
	25/9/57	Tower	Kiloton range	Maralinga	
	9/10/57	Balloon	Kiloton range	Maralinga	
GRAPPLE	8/11/57	Air	Megaton range	Christmas Island area	
GRAPPLE—1958 SERIES	28/4/58	Air	Megaton range	Christmas Island area	
	22/8/58	Balloon	Kiloton range	Christmas Island area	
	2/9/58	Air	Megaton range	Christmas Island area	
	11/9/58	Air	Megaton range	Christmas Island area	
	23/9/58	Balloon	Kiloton range	Christmas Island area	

JOINT UNITED KINGDOM-UNITED STATES NUCLEAR DETONATIONS

Date	Type of Burst	Yield	Location	Remarks
1/3/62	Underground	Low	Nevada Test Site	Announced by AEC as a joint United States-United Kingdom test of a British nuclear device.
7/12/62	Underground	Low	Nevada Test Site	Announced by AEC as a joint United States-United Kingdom test of a British nuclear device.

REPUBLIC OF FRANCE NUCLEAR DETONATIONS

Date	Type of Burst	Yield	Location	Remarks
13/2/60	Tower	60–70 KT	Reggan	Tower was 350 feet high; first test of a nuclear device by France.
1/4/60	Surface	Small	Reggan	
27/12/60	Tower	Small	Reggan	
25/4/61	Tower	Small	Reggan	
1/5/62	Underground	Medium	In Ekker	

U.S.S.R. NUCLEAR DETONATIONS

Date	Type of Burst	Yield	Location	Remarks
29/8/49	Atmospheric		USSR	First Russian nuclear detonation.
3/10/51*	Atmospheric		USSR	Statement by White House.
22/10/51*	Atmospheric		USSR	Statement by White House.
12/8/53	Atmospheric	Thermonuclear	USSR	Part of a series.
23/8/53	Atmospheric	Fission	USSR	Part of a series; energy release equivalent to type detonated at Nevada Test Site.
26/10/54*	Atmospheric		USSR	Statement by AEC; part of a series which began in mid-September and continued at intervals to the announcement date.
4/8/55*	Atmospheric		USSR	Statement by AEC; part of a series detonated in the preceding few days.
24/9/55*	Atmospheric		USSR	Statement by AEC; part of a series recently detonated.
10/11/55*	Atmospheric		USSR	Statement by AEC; part of a series recently detonated.
23/11/55*	Atmospheric	Megaton range	USSR	Statement by AEC; part of a series.
21/3/56*	Atmospheric		USSR	Statement by AEC; part of a series detonated in preceding few days.
2/4/56*	Atmospheric		USSR	Statement by AEC; part of a series detonated in preceding few days.
24/8/56	Atmospheric	Less than megaton	Siberia	Part of a series.
30/8/56	Atmospheric	Large	Siberia	Part of a series.
2/9/56	Atmospheric		USSR	Part of a series.
10/9/56	Atmospheric		USSR	Part of a series; announced by Soviet Union.
17/11/56	Atmospheric	Large	USSR	Part of a series.
19/1/57	Atmospheric		USSR	Part of a series.
8/3/57	Atmospheric		USSR	Part of a series.
3/4/57	Atmospheric		USSR	Part of a series.
6/4/57	Atmospheric		USSR	Part of a series.
10/4/57	Atmospheric	Large	USSR	Part of a series.
12/4/57	Atmospheric		USSR	Part of a series.
16/4/57	Atmospheric	Large	Siberia	Part of a series; largest tested so far in this series.
22/8/57	Atmospheric	Substantial	Siberia	
9/9/57*	Atmospheric	Moderate	Siberia	Statement by AEC; detonated within the preceding 2 days.
24/9/57	Atmospheric	Megaton range	Arctic	
6/10/57	Atmospheric	Thermonuclear	USSR	Announced by Soviet Union as a hydrogen device; AEC said it was of substantial size.
10/10/57	Atmospheric	Small	Arctic	

28/12/57	Atmospheric		Siberia	
23/2/58	Atmospheric	Megaton range	Arctic	
27/2/58	Atmospheric	Megaton range	Arctic	
27/2/58	Atmospheric	Large	Arctic	
14/3/58	Atmospheric	Below megaton range	Arctic	
14/3/58	Atmospheric	Below megaton range	Arctic	
15/3/58	Atmospheric	Below megaton range	Arctic	
20/3/58	Atmospheric	Small	Arctic	
21/3/58	Atmospheric		Siberia	This detonation was in a larger range than the test the day before.
22/3/58	Atmospheric	Medium	Arctic	
30/9/58	Atmospheric	Moderate to high	Arctic	
30/9/58	Atmospheric	Moderate to high	Arctic	
2/10/58	Atmospheric	Moderate	Arctic	
2/10/58	Atmospheric	Moderate	Arctic	
5/10/58	Atmospheric		Arctic	Smaller yield than the four immediately preceding detonations.
10/10/58	Atmospheric	Relatively large**	Arctic	
12/10/58	Atmospheric	Large**	Arctic	
15/10/58	Atmospheric	Large**	Arctic	
18/10/58	Atmospheric	Large**	Arctic	
19/10/58	Atmospheric	Small	Arctic	
20/10/58	Atmospheric	Large**	Arctic	
22/10/58	Atmospheric	Large**	Arctic	
24/10/58	Atmospheric	Large**	Arctic	
25/10/58	Atmospheric	Relatively large	Arctic	
1/11/58	Atmospheric	Relatively low	Siberia	
3/11/58	Atmospheric	Relatively low	Siberia	
1/9/61	Atmospheric	Intermediate range	Semipalatinsk	Announced by White House.
4/9/61	Atmospheric	Low kiloton range	Semipalatinsk	Announced by AEC.
5/9/61	Atmospheric	Low to intermediate range.	Semipalatinsk	Announced by AEC.
6/9/61	Atmospheric	Low to intermediate range.	East of Stalingrad	Announced by AEC.
10/9/61	Atmospheric	Order of several megatons.	Novaya Zemlya	Announced by AEC.
10/9/61	Atmospheric	Low to intermediate kiloton range.	Novaya Zemlya	Announced by AEC.
12/9/61	Atmospheric	Order of several megatons.	Novaya Zemlya	Announced by AEC.
13/9/61	Atmospheric	Low to intermediate range.	Semipalatinsk	Announced by AEC.
13/9/61	Atmospheric	Low to intermediate range.	Novaya Zemlya	Announced by AEC.
14/9/61	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
16/9/61	Atmospheric	Order of a megaton	Novaya Zemlya	Announced by AEC.
17/9/61	Atmospheric	Intermediate	Semipalatinsk	Announced by AEC.
18/9/61	Atmospheric	Order of a megaton	Novaya Zemlya	Announced by AEC.
20/9/61	Atmospheric	Order of a megaton	Novaya Zemlya	Announced by AEC.
22/9/61	Atmospheric	Order of a megaton	Novaya Zemlya	Announced by AEC.
2/10/61	Atmospheric	Order of a megaton	Novaya Zemlya	Announced by AEC.
4/10/61	Atmospheric	Order of several megatons.	Novaya Zemlya	Announced by AEC.
6/10/61	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
8/10/61	Atmospheric	Low yield range	Novaya Zemlya	Announced by AEC.

12/10/61	Atmospheric	Low to intermediate range.	Semipalatinsk	Announced by AEC.
20/10/61	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
23/10/61	Atmospheric	About 25 megatons	Novaya Zemlya	Announced by AEC.
23/10/61	Underwater	Low yield range	South of Novaya Zemlya.	Announced by AEC.
25/10/61	Atmospheric	Intermediate to high; probably less than a megaton.	Novaya Zemlya	Announced by AEC.
27/10/61	Atmospheric	Low to intermediate range.	Novaya Zemlya	Announced by AEC.
30/10/61	Atmospheric	58 megatons	Novaya Zemlya	Announced by AEC; detonated in vicinity of 12,000 feet.
31/10/61	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
31/10/61	Atmospheric	Intermediate to high yield range; probably below a megaton.	Novaya Zemlya	Announced by AEC.
2/11/61	Atmospheric	Low to intermediate range.	Novaya Zemlya	Announced by AEC.
2/11/61	Atmospheric	Low to intermediate range.	Novaya Zemlya	Announced by AEC.
4/11/61	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC. On Dec. 9, 1961, the AEC stated in a preliminary analysis of the recent Soviet nuclear test series that the Soviets had conducted approximately 50 atmospheric tests.
2/2/62	Underground	Well above the threshhold of underground detectability, even by a single national system.	Semipalatinsk	Announced by AEC as "apparently conducted."
5/8/62	Atmospheric	30 megatons	Novaya Zemlya	Announced by AEC. On Aug. 6, 1962, the Atomic Energy Commission stated that tests in the low kiloton range had been conducted a few days prior to the nuclear detonation of Aug. 5.
7/8/62	Atmospheric	Low kiloton range	Central Siberia	Announced by AEC.
10/8/62	Atmospheric	Less than one megaton	Novaya Zemlya	Announced by AEC.
20/8/62	Atmospheric	Order of several megatons.	Novaya Zemlya	Announced by AEC.
22/8/62	Atmospheric	Low megaton range	Novaya Zemlya	Announced by AEC.
25/8/62	Atmospheric	Order of several megatons.	Novaya Zemlya	Announced by AEC.
25/8/62	Atmospheric	Low	Semipalatinsk	Announced by AEC.
27/8/62	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
2/9/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
8/9/62	Atmospheric	Megaton range	Novaya Zemlya	AEC announcement said this was tenth specific test in current series, but all detected tests are not specifically announced, and a number of additional tests had been conducted.
15/9/62	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
16/9/62	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
18/9/62	Atmospheric	A few megatons	Novaya Zemlya	Announced by AEC.
19/9/62	Atmospheric	Multimegaton	Novaya Zemlya	Announced by AEC as second largest atmospheric test in current series, and fourth multimegaton test in past 5 days.
21/9/62	Atmospheric	A few megatons	Novaya Zemlya	Announced by AEC.
25/9/62	Atmospheric	Multimegaton	Novaya Zemlya	Announced by AEC as second largest in current series.
27/9/62	Atmospheric	Less than 30 megatons	Novaya Zemlya	Announced by AEC.
7/10/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.

14/10/62	Atmospheric	Low yield range	Semipalatinsk	Announced by AEC.
22/10/62	High altitude	A few hundred kilotons.	Central Asia	Announced by AEC.
22/10/62	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
27/10/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
28/10/62	High altitude	Intermediate range	Central Asia	Announced by AEC as similar to test conducted on Oct. 22.
28/10/62	Atmospheric	Low	Semipalatinsk	Announced by AEC.
29/10/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
30/10/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
1/11/62	High altitude	Intermediate range	Central Asia	Announced by AEC.
1/11/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
3/11/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
3/11/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
4/11/62	Atmospheric	Intermediate	Semipalatinsk	Announced by AEC.
17/11/62	Atmospheric	Low	Semipalatinsk	Announced by AEC.
18/12/62	Atmospheric	Intermediate	Novaya Zemlya	Announced by AEC.
18/12/62	Atmospheric	Intermediate	Novaya Zemlya	Announced by AEC.
20/12/62	Atmospheric	Low	Novaya Zemlya	Announced by AEC.
22/12/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
23/12/62	Atmospheric	See remarks	Novaya Zemlya	Dec. 26 AEC announcement said a number of atmospheric tests held Dec. 23–25. Largest about 20 MT, others low to a few megatons.
24/12/62	Atmospheric	About 20 megatons	Novaya Zemlya	
25/12/62	Atmospheric	See remarks	Novaya Zemlya	

*Date of announcement, not necessarily shot date.

**October 24, 1958, AEC announced that these test detonations had been of high yield, i.e., a yield in the probable megaton range.

NUCLEAR BOMB EFFECTS COMPUTER

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